CR-137927

SUMMARY REPORT

STUDY OF THE COST/BENEFIT TRADEOFFS FOR REDUCING THE ENERGY CONSUMPTION OF THE COMMERCIAL AIR TRANSPORTATION SYSTEM

(NASA-CR-137927) STUDY OF THE COST/BENEFIT TRADEOFFS FOR REDUCING THE ENERGY CONSUMPTION OF THE COMMERCIAL AIR TRANSPORTATION SYSTEM Summary Report, Nov. 1974 - Mar. 1976 (Lockheed-California Co., G3/03

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16. ABSTRACT

This study was performed to assess practical means for achieving reduced fuel consumption in commercial air transportation. Five areas were investigated: current aircraft types, revised operational procedures, modifications to current aircraft, derivatives of current aircraft and new near-term fuel conservative aircraft. As part of a multiparticipant coordinated effort, detailed performance and operating cost data in each of these areas were supplied to the contractor responsible for the overall analysis of the cost/benefit tradeoffs for reducing the energy consumption of the domestic commercial air transportation system.

A follow-on study was performed to assess the potential of an advanced turboprop transport aircraft concept. To provide a valid basis for comparison, an equivalent turbofan transport aircraft concept incorporating equal technology levels was also derived. The aircraft were compared on the basis of weight, size, fuel utilization, operational characteristics and costs.

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FOREWORD

This document, LR 27769-1, is the summary report of the Lockheed-California Company's contribution to a multicontractor analytical study entitled "Study of Cost/Benefit Tradeoffs For Reducing the Energy Consumption of the Commercial Air Transportation System" performed under Contract NAS 2-8612 for the National Aeronautics and Space Administration Ames Research Center, Moffett Field, California. The work summarized in this report includes work performed under the basic contract and work performed under the contract Modification Number 1 section entitled "Turboprop/Turbofan, Short/Medium Range Configuration Analysis". This report outlines the methods and presents the results and recommendations for further study emphasis. For details of both studies the reader is referred to Lockheed-California Company report LR 27769-2, NASA CR-137926, the contract final technical report dated August, 1976.

Mr. Louis J. Williams of the Research Aircraft Technology Office at the NASA Ames Research Center was the technical monitor and advisor for the study.

The study was performed within the Advanced Design and Technologies Division of the Lockheed-California Company, Burbank, California, under the leadership of Mr. John P. Hopkins, Study Manager.

Special mention and appreciation is hereby expressed in the memory of Mr. John C. Heitmeyer for his outstanding technical contributions, leadership and example as Lockheed Study Manager from the time of contract initiation until June 1975.

The Hamilton Standard and Pratt and Whitney Aircraft Divisions of United Technologies Corporation and Eastern Air Lines made major contributions to the Turboprop/Turbofan, Short/Medium Range Configuration Analysis section of Contract Modification Number 1. The Study Managers for these subcontractors were:

Mr. Bernard S. Gatzen - Hamilton Standard

Mr. David E. Gray - Pratt and Whitney Aircraft

Mr. R. Scott Stahr - Eastern Air Lines

TABLE OF CONTENTS

ILLUSTRATIONS

TABLES

TABLES (cont'd)

COST BENEFIT TRADEOFFS FOR REDUCING THE ENERGY
CONSUMPTION OF THE COMMERCIAL AIR TRANSPORTATION SYSTEM

J. P. Hopkins and H. E. Wharton

Lockheed-California Company

SUMMARY

This study examines the practical means for achieving reduced fuel consumption in commercial air transportation. A supplemental study performed as a modification to the basic contract assesses the merits of advanced turboprop propulsion.

Aircraft performance and operating cost data are developed in Phase I of the study under four basic options for fuel conservation. These basic fuel conserving options are operational procedure changes, modifications to and derivatives of current aircraft, and new near-term designs. Aircraft performance and operating cost data on current domestic fleet aircraft are developed to provide a baseline for comparison purposes. NASA Specification No. 2-24968 dated June 3, 1974, Statement of Work Study Task 1.4.1.1 specifies development of data on the Lockheed L-1011 and L-188 Electra as a minimum. Phase II consisted of selecting the most promising options, performing option refinements, and preparing the resulting data in a form suitable for use in the overall fleet analysis studies which were conducted by a transportation systems analysis consulting organization.

The merit of an advanced turboprop propulsion system designed to operate at high Mach numbers was evaluated by integrating it with an airframe system designed for 1985 service introduction and comparing it with an equivalent mission, equal technology turbofan powered airplane.

Conclusions and recommendations drawn from Lockheed's role in the basic study effort are as follows:

- Changes to operational procedures offer an immediate and inexpensive method to conserve fuel and should be implemented on a priority basis.

- Of the near-term L-1011 modifications studied, the engine afterbody revision and wing tip extension offer even larger fuel savings benefits than changes in operational procedures. The engine afterbody modification should be retrofitted to fleet aircraft, as well as the wing tip extension where possible (dictated by takeoff gross weight requirements).

- Increased seating capacity and/or density in terms of a modification to the basic L-1011-1 aircraft offers the most dramatic efficiency gains but is dependent on continuation of demand growth and fuel availability.

- New near-term aircraft designs are not likely to be developed without increased density seating. A later airplane service introduction to allow incorporation of more of the technology advances, including a new turboprop propulsion system, may enhance the case for a new aircraft development. Development of the advanced technologies required is recommended.

It was concluded from the supplemental studies that an advanced turboprop propulsion system is a viable alternative to the turbofan, offering significant fuel and operating cost savings without compromising passenger comfort. To accomplish this requires that the following actions be implemented on a first priority basis:

- Demonstrate propeller efficiency levels of approximately 80 percent (installed) at a flight Mach number of 0.80.

- Perform experimental investigations of propfan/turboprop wing integration to establish that reasonable drag characteristics exist for practical propfan/turboprop power plants mounted on swept, supercritical wings.

- Determine sound levels generated by propfan/turboprop concepts operating at Mach 0.80 cruise and establish sound attenuation and weight penalty requirements for their satisfactory suppression.

INTRODUCTION

The dependence of the United States on foreign sources of petroleum to meet our ever increasing energy demands was brought to the forefront in late 1973 by the oil embargo. The restrictions placed on all forms of energy consumption by the fuel allocations imposed during that period resulted in the consideration of and in some cases the actual conversion to alternative forms of energy. However, the air transportation industry is, now and for the foreseeable future, totally dependent on petroleum fuel. The restrictions of 1973 led to a concerted effort by the air transportation industry to conserve fuel. The effort did not diminish with the relaxation of the imposed allocations; the more than doubled fuel cost becoming the driving force for fuel conservation. To remain economically viable while continuing to meet the forecast increasing demand for service requires that the industry make every effort to conserve fuel.

The study summarized by this document examined the potential for improving the energy consumption of the commercial air transportation system from an airframe manufacturer's viewpoint. The Lockheed-California Company's share of this study was one part of a coordinated effort which included another airframe manufacturer, McDonnell Douglas, an airline operator, United Airlines, and a consultant organization specializing in air transportation economics and demand forecasting, United Technologies Research Center. The potential for fuel efficiency improvements in several specific areas was examined, followed by exploring the refinement of the most promising options. Characteristics, performance, operating cost and price information for the approved options were

provided by the airframe and airline contractors and used as inputs by the consulting organization. This latter effort included the overall analysis of the effects of introducing the fuel conserving options into demand projections and fleet operations models to arrive at a prediction of future fuel requirements, service levels and economics.

Baseline fuel and operating cost data were first established through tabulations of current fleet aircraft performance data on both a manufacturer's handbook basis and as reported to the Civil Aeronautics Board by the airline operators. The Lockheed L-1011 TriStar and L-188 Electra aircraft were studied as baseline aircraft in Task 1. Consideration of changes in operational procedures that result in improved fuel consumption was the Task 2 study effort. The Lockheed effort in this task was concentrated on the L-1011 aircraft. Task 3 was the preliminary design and evaluation of fuel conserving modifications to current aircraft, the modifications being limited to those that could be incorporated in current production or retrofitted to in-service aircraft. More extensive derivatives of current aircraft were considered in Task 4 followed by the design of all new, near-term fuel conservative aircraft in Task 5. Three payload/range size classes with both minimum direct operating cost and minimum fuel as design criteria were studied. In addition, both turbofan and turboprop propulsion systems were considered.

Because this study by necessity involved a coordinated effort among the several contractors and NASA, a study plan and study ground rules were established at the outset by the parties concerned. The study plan coordinating the work of all of the contractors was the responsibility of the consultant organization, United Technologies Research Center, and is discussed in their report. (Ref. 1). The NASA technical monitor, the airframe manufacturers, Lockheed and McDonnell Douglas, and the airline contractor, United Airlines, developed the study ground rules to be used in the aircraft performance and operating cost calculations. The flight profile used for all performance calculations is included as Figure 1 and the ground rules in terms of seating configurations, passenger and cargo allowances, and economic parameters is presented in Table 1.

A supplemental follow-on study, also summarized in this document, examines the potential viability of an advanced turboprop transport which was compared with an equal technology advanced turbofan transport. This effort resulted from a modification to the original contract in order to more fully explore the high potential fuel savings indicated for the turboprop transport aircraft concept in the preliminary studies. The aircraft analyzed were designed for service in 1985 and therefore incorporated additional fuel conserving technologies expected to be available in that time frame. Both turbofan and turboprop aircraft were designed to cruise at Mach 0.8, the turboprop utilizing an advanced propeller to accomplish this.

Three subcontractors, the Pratt and Whitney Aircraft and the Hamilton Standard Divisions of United Technologies Corporation, and Eastern Air Lines, assisted Lockheed in this supplemental study. Performance and economic ground rules consistent with the basic contract were maintained and preliminary data were supplied to the United Technologies Research Center for use in their air transportation system operations analysis studies.

Because of the large number of figures and tables required in the performance of this study, it was not practical to integrate them with the text material. Consequently, they have been sequentially incorporated at the end of the appropriate section, figures followed by tables.

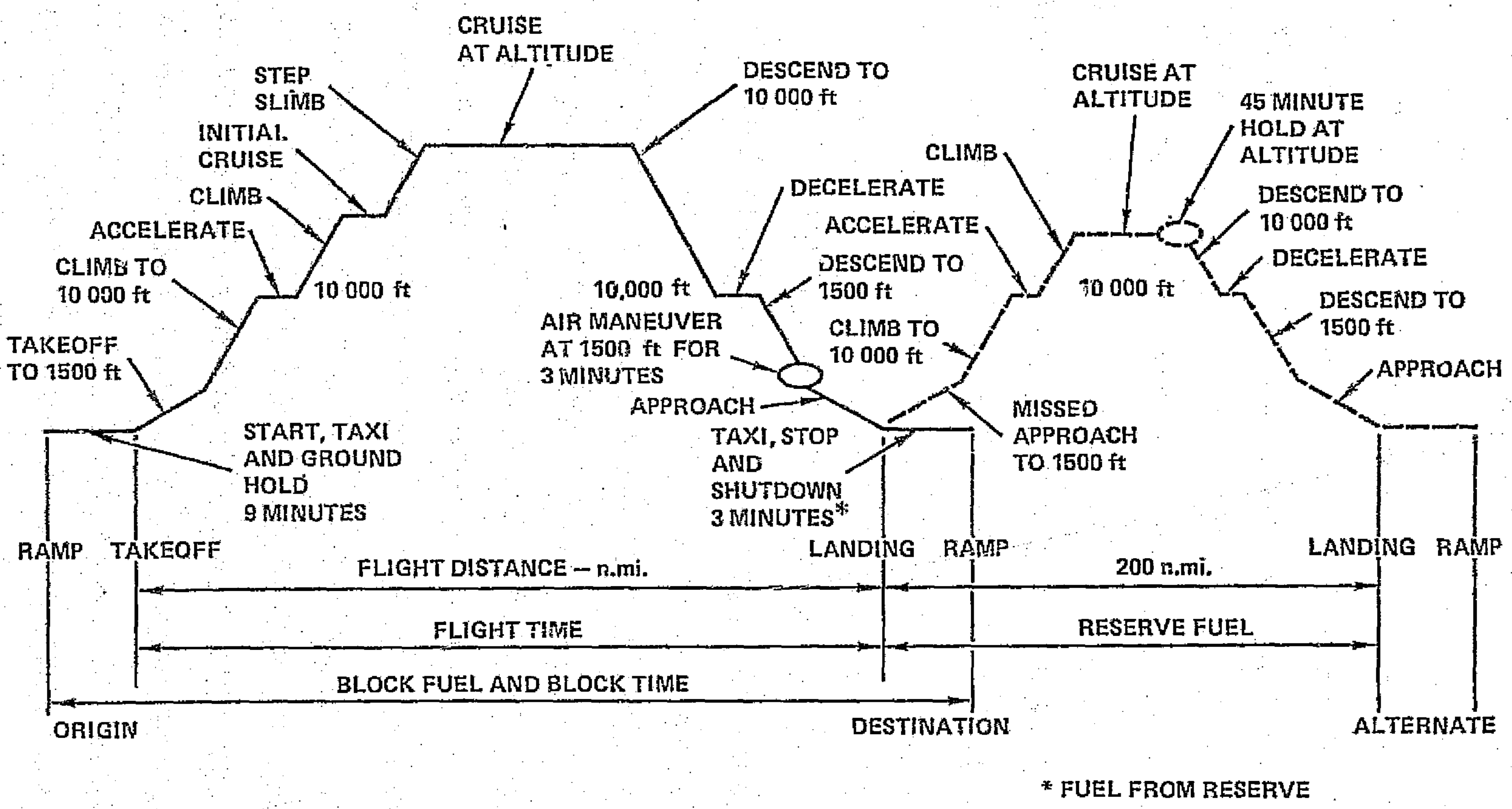


Figure 1.—Domestic mission flight profile

TABLE 1.- STUDY GROUND RULES

Interior Arrangements

- 10/90% First Class/Coach @ 38 in./34 in.
- 8 Abreast Seating (Baseline L-1011)
- Lower Deck Galley Where Feasible

Payload Allowances

- 200 lb/Passenger (Including Baggage)
- No Cargo Carried for Performance Analysis
- Cargo Revenue = 10% of Total Revenue
- Onboard Fuel Includes No Tankerage

Operational Parameters

- Load Factor = 58% (100% for New Aircraft Design)
- Fuel Heat Content = 18600 Btu/lb
- Fuel Density = 6.8 lb/gal
- Direct Operating Cost - Updated 1967 ATA
- Indirect Operating Cost - Lockheed 1973 Coefficients

Economic Parameters

- 1973 Dollars
- 15¢/Gallon Fuel (All Tasks)
- 15¢/30¢/60¢/Gallon Fuel - New Airplane Designs
- Depreciation Period = 16 Years with 10% Residual
- Spares = 15% of Flyaway Cost
- Insurance Rate = 1%
- Production Quantity = 250 Aircraft
- Inflation = 5%
- Discount Rate = 8%

ABBREVIATIONS/SYMBOLS/CONVERSIONS

Abbreviations

ASM	Airplane Seat Nautical Mile, Seat - n.mi.
ASSET	Advanced System Synthesis and Evaluation Technique (Lockheed computer program)
ASW	Antisubmarine warfare
ATA	Air Transport Association
ATC	Air Traffic Control
blk-hr	Block-hour
BPF	Blade passage frequency
Btu	British thermal unit
CAB	Civil Aeronautics Board
c.g.	Center of gravity
DOC	Direct operating cost
ECS	Environmental Control System
EPNdB	Equivalent perceived noise level, decibels
EPR	Engine overall pressure ratio
FAR	Federal Air Regulation
FC	First class passenger designation
flt-hr	Flight-hour
ft	Feet
fwd	Forward
gal	Gallon
GSE	Government-supplied equipment
IOC	Indirect operating cost
in.	Inch

IRAD	Independent research and development
KCAS	Calibrated airspeed, knots
KIAS	Indicated airspeed, knots
kt	knot
lb	Pound
LD-3	L-1011/DC-10 standardized half-size cargo container
LF	Load factor
LFL	Landing field length, ft
LRC	Long range cruise
MAC	Mean Aerodynamic Chord
MAD	Magnetic anomoly detection
MEW	Manufacturer's empty weight, lb
min	Minutes
MLG	Main landing gear
mph	Mile per hour
n.mi.	Nautical Mile
OEW	Operating empty weight, lb
Pax	Passenger
SFC	Specific fuel consumption, lb fuel/hr/lb thrust
shp	Shaft horsepower
SL	Sea level
SLS	Sea level static
TOFL	Takeoff field length, ft
TOGW	Takeoff gross weight, lb
Y	Tourist class passenger designation
UAL	United Airlines
UTRC	United Technologies Research Center
ZFW	Zero fuel weight, lb

Symbols

[illegible]	Aspect ratio, b^2/S
b	Wing span, ft
c	Wing chord, ft
C_D	Drag coefficient
C_L	Lift coefficient
D	Drag force, lb
dB	Decibel
F_N	Net thrust force, lb
f_r	Ring frequency, Hz
M	Mach number
q	Dynamic pressure, lb/ft^2
r_{LE}	Leading edge radius, in.
S	Wing area, ft^2
t/c	Thickness ratio
T/W	Thrust to weight ratio
V_T	True speed, kt
W/S	Wing loading, lb/ft^2
α	Angle of attack, degrees
η	Propeller efficiency
Λ	Wing sweep angle, degrees
ρc	Impedance of air

Conversions

To Convert From	To	Multiply By
Fahrenheit	Celsius	$t_c = (5/9)(t_F-32)$
foot	meter	0.3048
$foot^2$	$meter^2$	0.09290304
$foot^3$	$meter^3$	0.028316846592
foot/second	meter/second	0.3048
gallon	$meter^3$	0.003785411784
horsepower (550 ft-lb/s)	watt	745.69987
inch	meter	0.0254
knot	meter/second	0.5144444444
nautical mile	meter	1852
pound (force)	Newton	4.4482216152605
pound (mass)	kilogram	0.45359237

1. BASELINE TRISTAR AND ELECTRA AIRCRAFT DATA - TASK 1

The objective of this task is to establish the basis for comparison of the various fuel conserving options identified during the course of the study. Data for existing aircraft in the form of fuel consumption and operating costs were calculated using manufacturer's performance data and the standard flight profile ground rules established through agreement between NASA and the various contractor companies. The resulting calculated performance and cost data are compared with the airline-reported performance and cost data published annually by the Civil Aeronautics Board (CAB).

As stipulated by NASA Specification No. 2-24968 dated June 3, 1974, two Lockheed transport aircraft are considered; the L-1011 TriStar and the L-188 Electra. The calculated data for both aircraft are based on the use of the high-speed flight profiles which are representative of the typical airline operation for these aircraft prior to the September 1973 oil embargo by the OPEC countries; that period generally referred to as pre-energy crisis. The United States trunk airlines are required to report financial and operating statistics to the CAB in accordance with a uniform system (Form 41) and these data are summarized by the CAB in the Aircraft Operating Cost and Performance Report (Ref. 2). This report is the source of the airline operations data referred to in this section as CAB data.

For the base study year, 1973, two domestic airlines, Trans World and Eastern, operated the L-1011 TriStar. Since the route structures of these airlines are quite different, the CAB data for both are used. A comparison of the calculated fuel consumption and operating cost data and the data as reported by the CAB is shown in Figure 2 where the symbols representing the reported CAB data are plotted at the CAB average stage length for each airline.

Reference to Figure 2 shows significantly higher fuel consumption and cost exhibited by the CAB data. This is not unexpected and in fact is typical of comparisons made between ideal and in-service performance levels. Air traffic control delays and routing, weather and performance deterioration are all a part of the difference. In addition, the reporting year 1973 was a period when the L-1011 was in its introductory service phase which included considerable operating time with an interim engine.

During the base study year of 1973, the Electra saw only limited airline service. The type of service which the aircraft provided, shuttle and backup to first line aircraft, was also considered to be nonrepresentative for purposes of this study. An earlier year, 1967, was selected for establishing the baseline data. That year represents an Electra operational period that is well down the learning curve, approximately ten years after initial airline service, thus eliminating any erratic performance and cost data caused by new airplane introduction. The CAB cost data are also directly comparable to the calculated costs based on the 1967 ATA methods.

In order to obtain a good representation of the L-188 Electra operating data, CAB data for six airlines were assembled. These data as well as the average data are compared to the calculated levels in Figure 3. Although differences are still apparent, especially in the direct operating costs for particular airlines, the comparison between the average CAB data and the calculated data shows a better correlation than the L-1011 results. The difference in phase of service life of the two aircraft for the study years chosen is undoubtedly the major cause of this difference in the comparisons.

At this stage of the study it had been determined that the manufacturer's data for all tasks should be based on handbook performance levels. For the systems analysis performed by UAL and UTRC, block fuel and block time adjustment factors were used to convert the handbook data to expected operational levels. These adjustments were developed by comparing the manufacturer's handbook data with current UAL in-service operational experience and are discussed further in Section 6 of this report and in Reference 3. The reader is referred to the companion final report, Reference 4, for further details of the CAB/idealized data comparison.

Tables 2 through 5 present the fuel consumption and operating cost data as calculated for the L-1011 TriStar. These data are tabulated for a series of stage lengths including the 1973 CAB average stage length. Fuel consumption is shown in terms of total block fuel and on both an airplane-nautical mile and a seat-nautical mile basis in Table 2. The seat-nautical mile fuel consumption is shown in units of seat-nautical miles per gallon and Btu's per seat-nautical mile. Total direct and total indirect operating costs are tabulated in Table 3 while the detailed breakdowns of these costs are shown in Tables 4 and 5. All of the cost data are presented in units of cents per available seat-nautical mile. In addition, the total cost data are presented in Table 3 in terms of dollars per block hour with the corresponding block speed at each stage length indicated in an adjacent column. The format of the data shown in Table 2 and 3 is typical of that used for the data provided for each of the various aircraft configurations and models presented in the remaining sections of this summary report. For brevity, the detailed direct and indirect cost breakdowns typified by Tables 4 and 5 are omitted from the remaining sections of this report. A complete set of these data are included in the study final report (Ref. 4).

In the case of the L-188 Electra, Table 6 presents the calculated fuel consumption data for various stage lengths. Since the calculated cost data for the Electra were based on the year 1967 rather than the base study year of 1973 and were used only for comparison with the CAB data, they are omitted here with NASA concurrence.

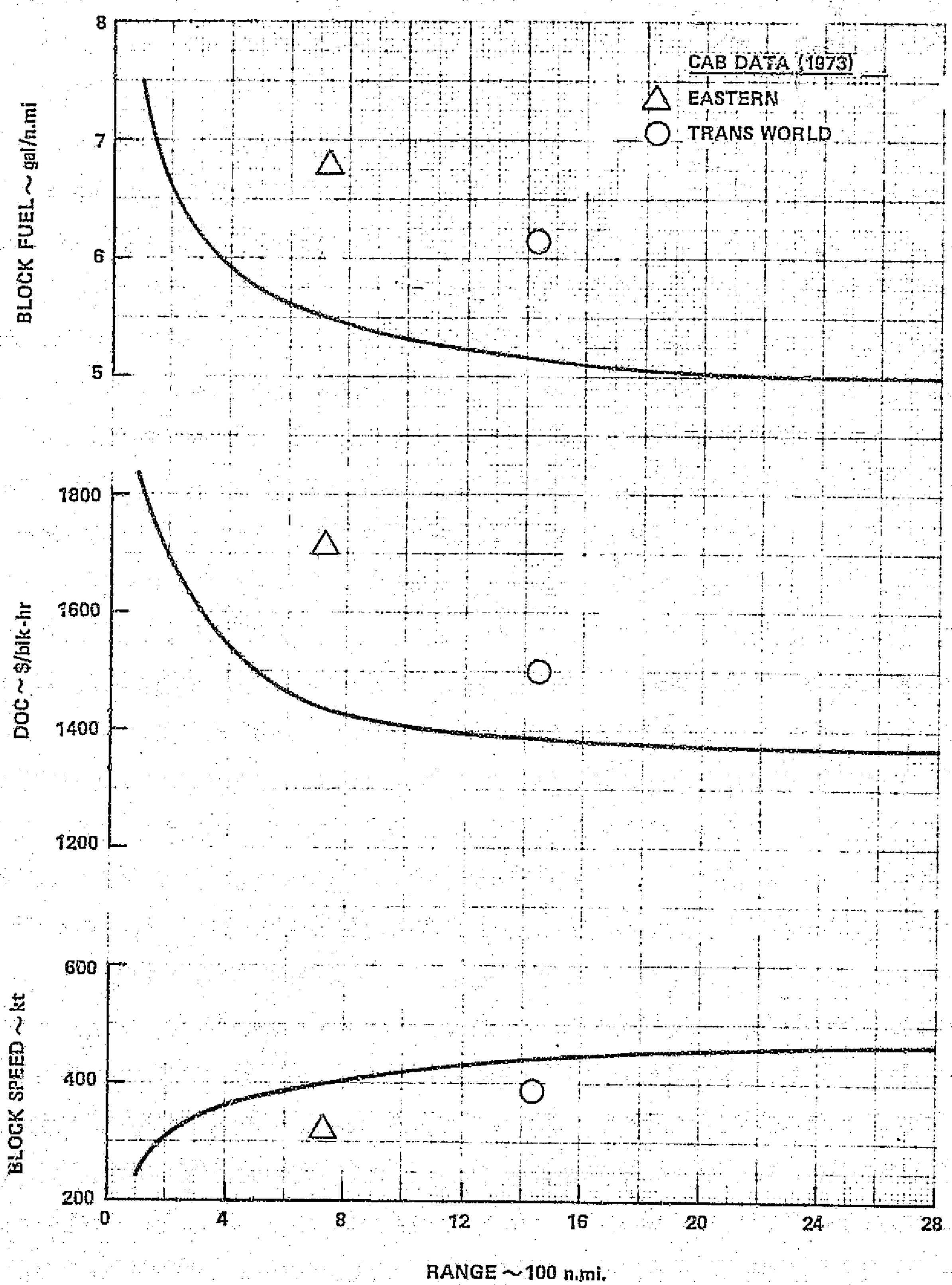


Figure 2.—Comparison of calculated and CAB data - L-1011 TriStar

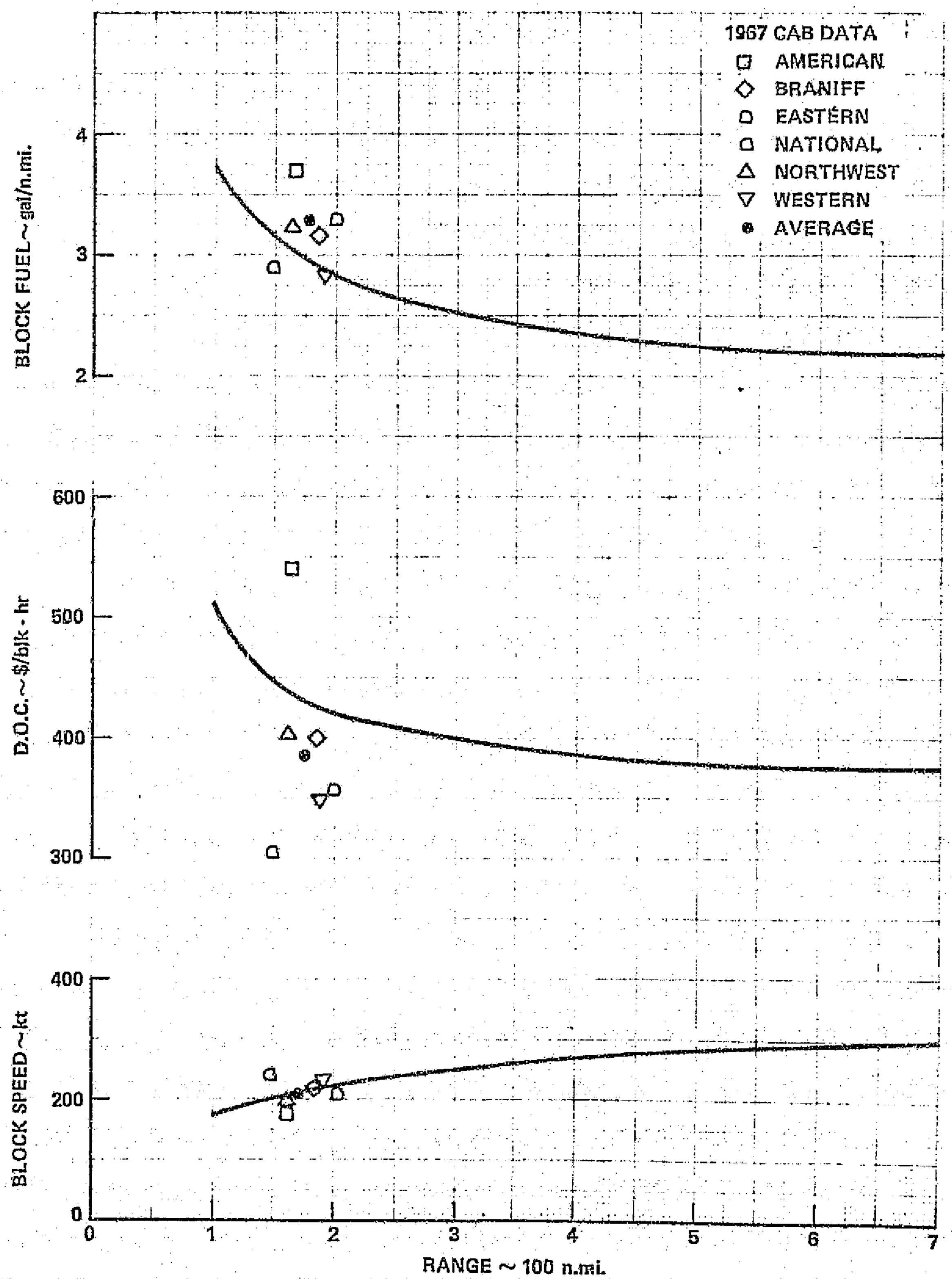


Figure 3.—Comparison of calculated and CAB data - L-188 Electra

TABLE 2.- CALCULATED FUEL CONSUMPTION - L-1011 TRISTAR PRE-ENERGY CRISIS

Stage Length n.mi.	Block Fuel Consumption			
	lb	gal/n.mi.	seat-n.mi./gal	Btu/seat-n.mi.
100	5 107	7.51	36.35	3480
200	8 938	6.57	41.55	3044
400	16 010	5.89	46.35	2729
600	23 082	5.66	48.23	2622
1000	36 538	5.37	50.81	2489
2000	68 754	5.06	54.00	2342
3000	101 952	5.00	54.60	2316
4000	138 981	5.11	53.42	2368
825	30 855	5.50	49.60	2550

TABLE 3.- CALCULATED TOTAL OPERATING COSTS - L-1011 TRISTAR PRE-ENERGY CRISIS

Stage Length n.mi.	Block Speed kt	Total DOC		Total IOC	
		\$/blk-hr	¢/seat-n.mi.	\$/blk-hr	¢/seat-n.mi.
100	240	1824	2.81	5512	8.48
200	305	1690	2.04	3650	4.41
400	360	1538	1.56	2530	2.57
600	388	1464	1.39	2028	1.92
1000	414	1412	1.25	1567	1.39
2000	449	1374	1.12	1201	0.98
3000	465	1366	1.08	1068	0.84
4000	472	1368	1.06	1080	0.84
825	405	1428	1.30	1735	1.57

TABLE 4.- DIRECT OPERATING COST BREAKDOWN - L-1011 TRISTAR PRE-ENERGY CRISIS

DOC Component / Stage Length (n.mi.)	DOC ¢/seat-n.mi.								
	100	200	400	600	1000	2000	3000	4000	825
Crew	0.41	0.34	0.27	0.25	0.23	0.21	0.21	0.20	0.24
Insurance	0.09	0.08	0.07	0.06	0.05	0.05	0.05	0.04	0.05
Depreciation	0.61	0.52	0.41	0.37	0.35	0.32	0.31	0.30	0.36
Maintenance	1.29	0.71	0.48	0.40	0.32	0.26	0.24	0.24	0.34
Fuel (15¢/gal)	0.42	0.39	0.33	0.32	0.30	0.28	0.28	0.28	0.31
Total DOC	2.81	2.04	1.56	1.39	1.25	1.12	1.08	1.06	1.30

TABLE 5.- INDIRECT OPERATING COST BREAKDOWN - L-1011 TRISTAR PRE-ENERGY CRISIS

IOC Component / Stage Length (n.mi.)	IOC ¢/seat-n.mi.								
	100	200	400	600	1000	2000	3000	4000	825
System Expense	0.15	0.12	0.07	0.04	0.04	0.03	0.03	0.02	0.04
Local Expense	2.32	0.97	0.49	0.39	0.23	0.12	0.08	0.08	0.29
A/C Control Expense	0.07	0.04	0.02	0.01	0.01	0.01	0.01	0.01	0.01
Hostess Expense	0.28	0.25	0.21	0.17	0.16	0.15	0.14	0.14	0.16
Food and Beverage	0.27	0.24	0.20	0.17	0.16	0.15	0.14	0.14	0.16
Passenger Service	3.14	1.40	0.79	0.52	0.31	0.16	0.11	0.10	0.36
Cargo Handling	1.50	0.80	0.40	0.25	0.15	0.08	0.05	0.05	0.19
Other Passenger Expense	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22
Other Cargo Expense	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
General and Administration	0.53	0.36	0.16	0.15	0.11	0.09	0.08	0.07	0.13
Total IOC	8.48	4.41	2.57	1.92	1.39	0.98	0.84	0.84	1.57

TABLE 6.- CALCULATED FUEL CONSUMPTION - L-188 ELECTRA

Stage Length n.mi.	Block Fuel Consumption			
	lb	$\frac{\text{gal}}{\text{n.mi.}}$	$\frac{\text{seat-n.mi.}}{\text{gal}}$	$\frac{\text{Btu}}{\text{seat-n.mi.}}$
100	2 500	3.68	23.10	5475
200	3 800	2.79	30.47	4151
400	6 500	2.39	35.56	3557
600	9 000	2.21	38.46	3289
1000	14 000	2.06	41.26	3065
1500	20 300	1.99	42.71	2961
2000	26 800	1.97	43.15	2931
2300	30 500	1.95	43.59	2902
176	3 480	2.91	28.18	4485

2. TRISTAR FUEL CONSERVING OPERATIONAL PROCEDURES - TASK 2

The impact of operational procedures on the fuel usage of the L-1011 was investigated in this task. Fuel allocations following the oil embargo of 1973 forced the airlines to place more emphasis on fuel conservative operational procedures as a primary consideration in everyday operation. Prior to this time period, most airlines directed attention to procedures for saving fuel for purely economic reasons. Many identifiable fuel saving operational procedures noted in this study were implemented by certain airlines or all airlines before or during the course of this study. However, since identification of all fuel conserving procedures and the associated potential fuel savings were required in this task, the fact that a particular procedure was already in use was not used as a basis for exclusion.

Operational procedures that are available to the airlines for fuel savings were divided into two categories; flight profile management and aircraft configuration management. The first category encompasses those procedures which relate directly to the way the airplane is flown; all segments of the flight profile being examined to identify procedures which offer fuel savings. The second category, aircraft configuration management, includes maintenance-related items which can affect the performance of the airplane and also use-related procedures or procedures which may have in the past been determined by airline policy but which with changes can result in a net fuel savings.

Both the flight profile and aircraft configuration management categories of procedures include options over which the airline operator has some degree of control. Mitigating against some of these options are the limitations imposed by the equipment itself and the environment within which the airline must operate. Although the airline has no primary control over these externalities, they were included in this task since in many cases they can determine whether or to what extent certain fuel saving operational procedures can be implemented or should be implemented.

The fuel conserving operational procedures considered in these three categories are as follows:

Flight Profile Management

- Cruise Speed
- Cruise Altitude
- Climb Speed
- Descent Speed
- Takeoff
- Landing

Aircraft Configuration Management

- Gross Weight Control
  - Reserves
  - Tankerage
  - Operating Empty Weight
- Center of Gravity Control
- Aircraft Cleanliness

Externalities

- Engine Deterioration
- Air Traffic Control

The most significant payoffs in the flight profile management category in terms of fuel savings are in the cruise speed and cruise altitude selection. Since on the majority of flights, the airplane is operated in cruise for the largest percentage of the total mission time, small gains in fuel efficiency result in the most significant improvements in terms of block fuel usage. Therefore, any procedure which can be used to ensure that the airplane is operated at optimum speed and altitude during cruise offers good potential for reduction in overall fuel usage. In terms of percentage of block fuel, the other items included under flight profile management offer smaller savings. Except on the shorter stage lengths, the time spent in the takeoff, landing, climb, and descent phases of the flight are minimal, and, therefore, the large benefit from small increment fuel consumption improvement is not available.

The second category of fuel conserving procedures, aircraft configuration management, relates to those items of the aircraft configuration, both internal and external, which can affect the fuel consumption. In this category, gross weight control offers the most powerful means of saving fuel. Reductions in empty weight are effective on every flight operated with the aircraft and therefore result in large cumulative savings. Because of this cumulative effect, maintenance of the aerodynamic integrity of the airplane through repair of damaged surfaces and seals also offers potential for fuel savings.

The final fuel savings category, externalities, includes consideration of the air traffic control system which has the largest effect on the ability of an airline to implement fuel conserving procedures. Improvements in the air traffic control system offer significant potential for fuel savings by allowing day-to-day operations more closely approximating the optimum. In this study, reasonably attainable fuel savings with an improved air traffic control system were identified. Determination of the cost of the required changes to the system and the associated cost/benefit assessment are beyond the scope of this study.

The final technical report, Reference 4, discusses each of the fuel saving procedures identified above in more detail.

The assemblage of fuel-savings data to satisfy the requirements of the forecast studies involved a cooperative effort between the manufacturers and the airline contractor. To accomplish this, the fuel savings for the identified operational procedures changes were calculated by the manufacturers for their respective aircraft models. These identified changes were then combined and a list of block fuel reductions, with and without ATC improvements, was developed for each aircraft designated by NASA for use in the air transportation system analysis study. In this task, the Lockheed generated data for the L-1011 were combined with the McDonnell Douglas generated DC-10 data for use by UTRC in the current three engine wide-bodied aircraft class. Figure 4 illustrates the relationship between the agreed to fuel savings and those identified for the L-1011.

During the preparation of the data discussed above, the fuel consumption and operating cost data for the L-1011 with selected operational procedure changes were generated. Although these data were not used directly in the air transportation system analysis study, they are presented in this section for completeness. The format and presentation are the same as that used for the L-1011 data of Task 1. Fuel consumption and operating cost for the L-1011 as operated in 1975 are presented in Tables 7 and 8. In the 1973 baseline flight profile of Task 1, the airplane was flown along a high-speed climb and cruise profile. For the 1975 Basis of Tables 7 and 8, the climb speeds were slowed to the long-range schedule and the cruise speed was reduced from the pre-energy crisis Mach 0.85 to Mach 0.82. These changes are considered to be representative of the steps which were taken by the airlines to save fuel following the oil embargo. This level of performance is also considered to be representative of the current operation of the aircraft on a handbook basis. Tables 9 and 10 present the fuel consumption and operating cost data for the L-1011 assuming that some additional procedure changes are implemented. Included in these data are the low-speed climb and Mach 0.82 cruise of the 1975 basis L-1011 and in addition a general aerodynamic cleanup, a one percent aft movement of the center of gravity and a two thousand foot step-climb cruise. This cruise procedure would necessitate a change in the current altitude separation criteria: the current 2000 feet would have to be reduced to 1000 feet.

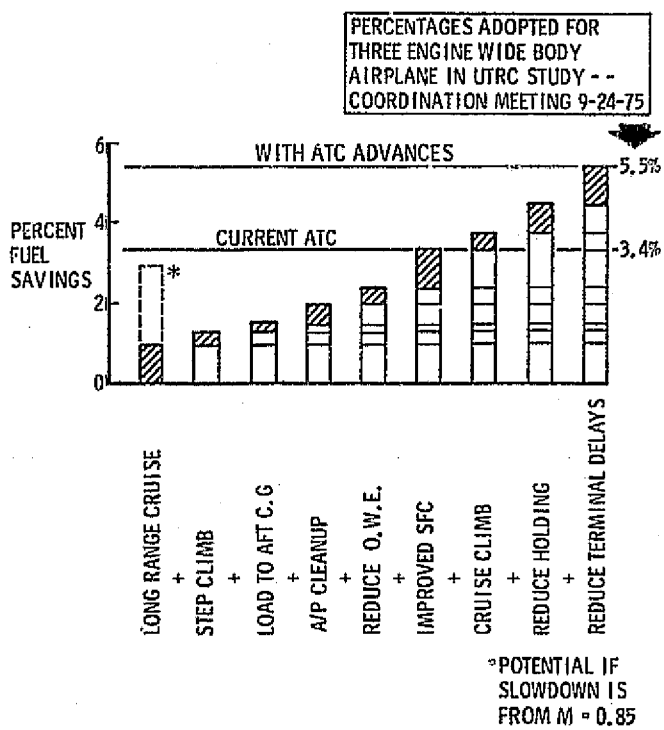


Figure 4.—L-1011 operational procedures fuel savings summary

TABLE 7.- CALCULATED FUEL CONSUMPTION - L-1011 TRISTAR (1975 BASIS)

Stage Length n.mi.	Block Fuel Consumption			
	lb	gal / n.mi.	seat-n.mi. / gal	Btu / seat-n.mi.
100	5 089	7.48	36.50	3465
200	8 893	6.54	41.74	3030
400	15 871	5.84	46.79	2703
600	22 805	5.59	48.84	2590
1000	35 906	5.28	51.70	2446
2000	67 049	4.93	55.38	2284
3000	98 893	4.85	56.32	2246
4136	139 300	4.95	55.12	2295
825	30 294	5.40	50.52	2515

TABLE 8.- CALCULATED TOTAL OPERATING COSTS - L-1011 TRISTAR (1975 BASIS)

Stage Length n.mi.	Block Speed kt	Total DOC		Total IOC	
		\$/blk-hr	¢/seat-n.mi.	\$/blk-hr	¢/seat-n.mi.
100	233	1803	2.84	5394	8.50
200	296	1664	2.07	3730	4.65
400	349	1514	1.59	2540	2.67
600	376	1444	1.41	1978	1.93
1000	402	1396	1.27	1539	1.40
2000	436	1354	1.14	1177	0.99
3000	451	1338	1.10	1040	0.86
4136	458	1334	1.07	1050	0.84
825	392	1420	1.32	1675	1.56

TABLE 9.- CALCULATED FUEL CONSUMPTION - L-1011
WITH CHANGES IN OPERATIONAL PROCEDURES

Stage Length n.mi.	Block Fuel Consumption			
	lb	gal/n.mi.	seat-n.mi/gal	Btu/seat-n.mi.
100	5 002	7.36	37.11	3408
200	8 731	6.42	42.52	2974
400	15 471	5.69	48.00	2635
600	22 148	5.43	50.29	2515
1000	34 455	5.07	53.88	2347
2000	62 074	4.56	59.81	2115
3000	93 602	4.59	59.50	2126
4300	141 500	4.84	56.41	2242
825	29 340	5.23	52.40	2420

TABLE 10.- CALCULATED TOTAL OPERATING COSTS - L-1011
WITH CHANGES IN OPERATIONAL PROCEDURES

Stage Length n.mi.	Block Speed kt	Total DOC		Total IOC	
		$/blk-hr	¢/seat-n.mi.	$/blk-hr	¢/seat-n.mi.
100	233	1799	2.83	5394	8.50
200	294	1660	2.07	3630	4.52
400	354	1507	1.56	2480	2.57
600	375	1436	1.40	1978	1.93
1000	400	138[illegible]	1.26	1530	1.40
2000	437	1330	1.12	1178	0.99
3000	451	1325	1.08	1048	0.85
4300	460	1343	1.07	1060	0.84
825	392	1400	1.32	1685	1.59

3. TRISTAR FUEL SAVINGS MODIFICATIONS - TASK 3

Fuel conserving modifications of the L-1011 were studied in this task. For purposes of the study, modifications were defined as those fuel conserving improvements which could be incorporated either in new production airplanes or as retrofits to already delivered airplanes and were not of such a drastic nature as to remove the airplane from service for an undue length of time. An additional criterion was that the modifications were not so costly as to negate any fuel savings that might be identified; i.e., the modification must be cost effective.

Potential modifications identified at the beginning of the study to be considered in this task were as follows:

- Wing tip treatment
- Propulsion improvements
- Increased seating density
- Less sophisticated high-lift devices
- Wing leading edge modifications

During the course of the study some of these modifications proved to be impractical and were therefore eliminated. On the other hand, study of these particular modifications led to the discovery of other potential fuel saving modifications.

The initial modification considered in this study task was an increase in the aspect ratio of the L-1011 wing through a treatment of the wing tip. Fuel savings would be inherent due to a reduction in both cruise and second segment climb drag. A planar tip extension as well as a winglet were considered. The results of an experimental and analytical study conducted at Lockheed with independent development funds were drawn upon for this study subtask (Ref. 5). The experimental study involved wind tunnel tests of a 1/30 scale L-1011 model in both the Lockheed 8 by 12 foot low-speed and 4 by 4 foot transonic/supersonic tunnels. The wind tunnel models are shown in Figure 5.

The results of the experimental study showed that transonic flow effects severely degrade the performance of the winglet as compared to the tip extensions. A winglet which gave the same drag reduction as a comparable tip extension at low Mach number (M 0.2) was able to reduce the drag only one-half as much as the tip extension at cruise Mach number. On the basis of the net drag reduction per bending moment increase, the tip extension is the more efficient system. The wind tunnel tests also indicated that the winglet gave a rapid increase in drag at the higher Mach numbers which would indicate reduced operational buffet limits and higher Mach induced buffet loads at operational limit speeds.

Several other areas such as high lift performance, handling qualities, flutter and aeroelastic effects, manufacturing costs and loads analysis have to be considered in selecting between the winglet and the tip extension as drag reducing devices in an airplane design. In the case of the tip extension, the investigation of these items is straightforward and well understood, whereas the impact of the winglet on many of these items is not known at the present time. This additional technological risk in the case of the winglet plus the unfavorable characteristics exhibited in the wind tunnel tests led to the recommendation that a planar tip extension be used as a modification to improve the fuel efficiency of the L-1011.

A three foot per side wing tip extension was selected for this study. With a three foot extension, a three percent reduction in fuel consumption can be obtained and minimal wing structure changes are involved. For retrofit on in-service L-1011's, no rework or strengthening of the wing is required, however, a reduction in maximum takeoff weight from 430 000 pounds to 410 000 pounds will be required. For operators whose route structures do not require full takeoff gross weight, this retrofit may be suitable. Where full takeoff weight is required and the additional down-time and cost can be accepted, additional wing structural changes would allow retention of the 430 000 pound limit.

Table 11 and 12 present the fuel consumption and operating cost data for the L-1011 with the three-foot wing tip extension. These data are tabulated for a series of stage lengths including the 1973 CAB average stage length as in Section 2. Note, however, that the maximum stage length shown is reduced somewhat from the basic L-1011 data presented earlier. This is caused by the reduced takeoff gross weight capability with the simplified tip modification used. The long-range climb and Mach 0.82 cruise performance are reflected in the data of Tables 11 and 12. This is consistent with the current (1975) operation of the airplane, as discussed in Section 2.

The engine offers perhaps the best opportunity for cost effective modifications to improve fuel consumption. Flight test costs alone can consume the potential savings of aircraft external aerodynamic modifications. For engine modifications, the certification flight testing required is usually not as extensive, since items such as aircraft handling qualities, stall characteristics and performance may not be required. Thus a gain of one percent in terms of engine specifics can be more cost effective than one percent gained through an external configuration modification.

Continuing research at Rolls Royce has identified fuel flow reductions on the order of two percent for improvements in internal components of the RB.211 engine. These modifications which consist mainly of revised sealing and improved tip clearances to reduce leakage in the core engine could be incorporated by 1978. Additional fuel flow reductions of up to four percent could be realized in the 1982 time period through the incorporation of a mixed-flow exhaust and additional engine sealing.

A large improvement in the specific range of the L-1011 is achievable through revision of the engine afterbody. The original afterbody configuration on the L-1011 incorporated a hot stream spoiler which deflected the core engine flow when reverse thrust was selected. Since the core engine reverse thrust contribution is very small due to the high bypass ratio of the RB.211, the performance effect of eliminating the hot stream spoilers is not significant. Removing the spoilers allows revision to the external contours of the engine afterbody; the fairings or stangs are removed and the core nozzle is reshaped which, combined with a lengthening and reshaping of the fan duct, allows improved flow over the afterbody. These changes are illustrated in Figure 6 which compares the original afterbody configuration with the modified 15 degree afterbody design. The center engine installation is shown; the wing engine installation is similar.

Flight tests with the 15 degree engine afterbodies showed a 3.4 percent improvement in fuel consumption out to a Mach number of 0.83. At higher Mach numbers even more significant savings were indicated caused by a delay in the drag rise characteristics.

Table 13 and 14 present the fuel consumption and operating cost data for the L-1011 incorporating 15 degree engine afterbodies. The presentation is as shown in the previous section, including the use of the long-range climb and Mach 0.82 cruise. The data of Tables 13 and 14 include only the improvement due to the 15 degree engine afterbody and do not include the additional potential of the internal engine improvements discussed above.

A study of the potential for fuel saving through increased seating density in the basic L-1011-1 was accomplished. Under the study ground rules with a 10/90 split, 8 abreast seating configuration, the L-1011 carries 276 seats. The airplane has been certificated for as many as 400 passengers. Attaining this high seating capacity involves 10 abreast seating with a tight seat pitch of 30 inches. While this configuration would probably not be acceptable to domestic operators, it gives an indication of the upper limits of increased density in the L-1011 fuselage size.

The potential for fuel savings with the increased seating density approach lies in the additional seats flown for each unit of fuel. This provides savings in operating cost. Figure 7 shows that in a typical 2000-nautical mile L-1011 mission, very large fuel savings can be attained with increased seating. However, to retain consistency in the study an improvement of eight percent was calculated as being the attainable fuel savings while still complying with the seating-mix of the study. The eight percent savings could be accomplished, for example, by incorporating below deck seating for sixteen additional passengers. Below deck capability is included here as an indication of what could be done within the context of the study ground rules and to establish a reasonable quantitative estimate of the potential fuel savings that can be realized through increased seating density. The same savings in seat-miles per gallon could be attained by relaxing the study ground rules in terms of seat pitch and/or first class/tourist mix.

While seating density can have a dramatic effect on the seat-mile per gallon figure attainable, the practicality of this approach needs to be assessed. Definite fuel savings could be identified by substitution of high density aircraft on a study route structure but flying these same aircraft in an actual airline operation with a fixed number of passengers offers no real savings. With increased demand, this option offers very real benefits, and, in addition, it is an aircraft modification that can be accomplished in a short time period for minimum cost by the airline operator. Identification of where and when this particular fuel saving modification might be incorporated was deferred to the air transportation system analysis studies.

Elimination of portions of the high lift system of the basic L-1011 was considered in this task as a means of decreasing the operating empty weight. Company funded wind tunnel tests were used to verify whether the flaps-deleted configurations were compatible with the lift and stability requirements of the airplane. It was determined however that elimination of any of the flap segments, leading or trailing edge, was undesirable either on the basis of airplane performance or cost effectiveness. In addition, since the wind tunnel results indicated that the present leading edge slats are required to maintain suitable stability and performance characteristics, incorporation of a leading edge glove was eliminated from consideration.

Consideration of the wing leading edge modifications led to a study of the effectiveness of the leading edge slats as installed on the production airplane. Flight tests have confirmed that a small amount of leakage is present between the lower and upper wing surfaces in the area of the leading edge slats. Improved inboard slat hold-downs and improved lower surface trailing edge slat seals have been tested and provide an improvement of 0.5 percent in the L-1011 cruise performance.

At the conclusion of this study task, the following modifications were recommended for incorporation into the L-1011 fleet: 15° engine afterbodies, drag cleanup, extended wing tips, and internal propulsion improvements. The fuel savings identified for each of these modifications are summarized in Figure 8. The savings to be expected for the three time periods; 1975, 1978, and 1985, are indicated.

NASA designated McDonnell Douglas as the contractor responsible for summarizing the fuel savings and cost information for the modification options to be used by UTRC in the air transportation system analysis studies. In the UTRC study, the L-1011 and DC-10 were combined in the three-engined wide body class. Since the modifications to the DC-10 resulted in fuel savings approximately equal to those identified for the L-1011, the figure of 7.5 percent as indicated in Figure 8 was adopted for the UTRC studies.

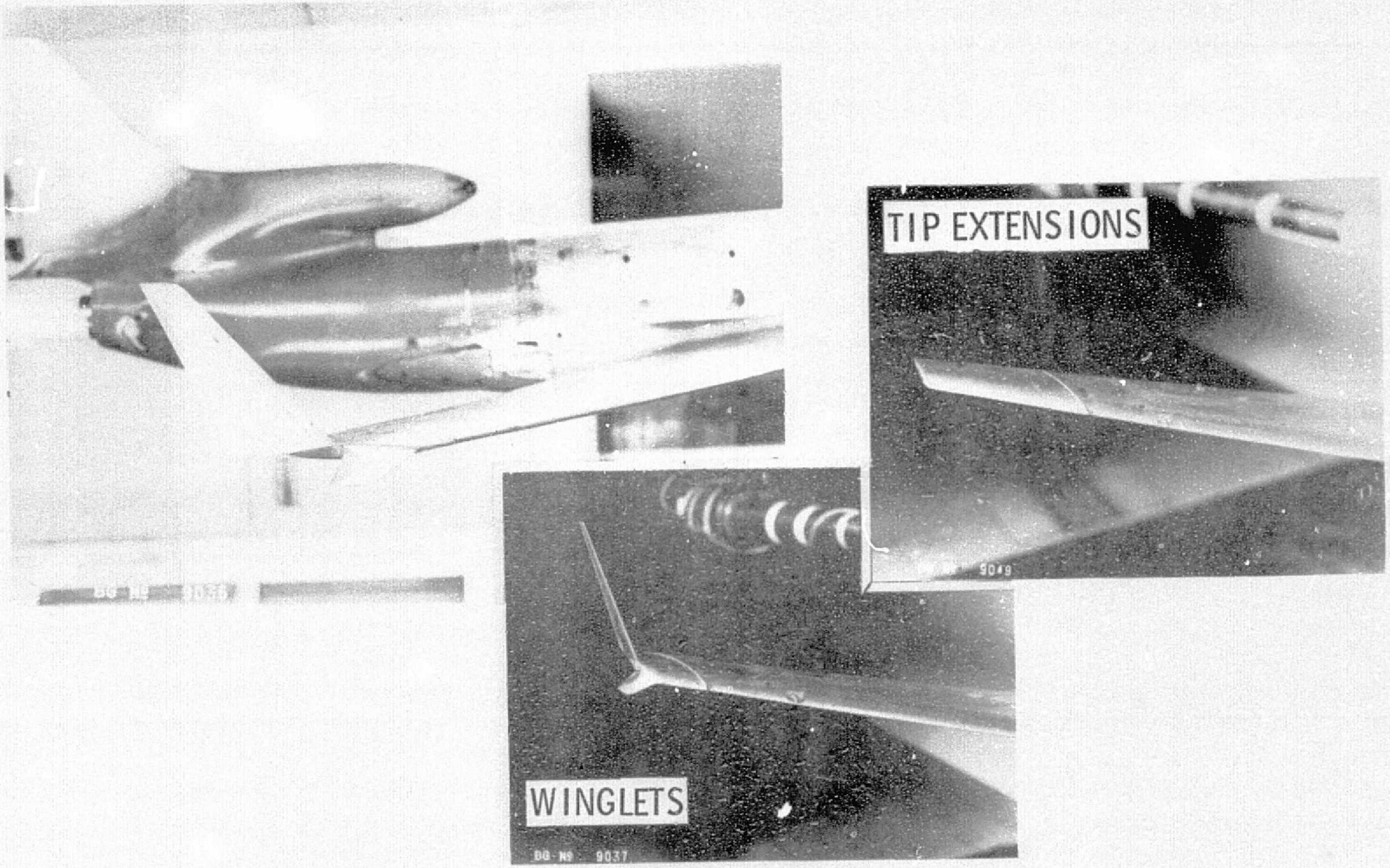
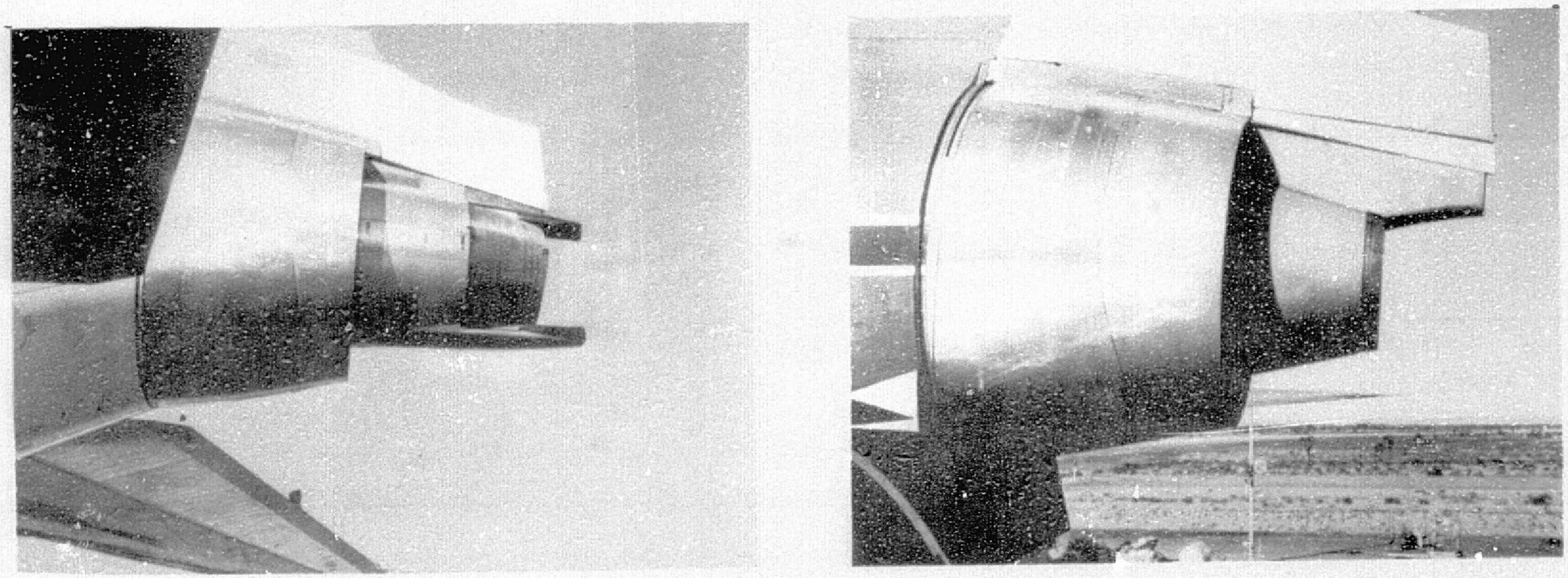


Figure 5.—L-1011 wing tip wind tunnel model



BEFORE AFTER

Figure 6.—RB.211 engine afterbody revision, L-1011

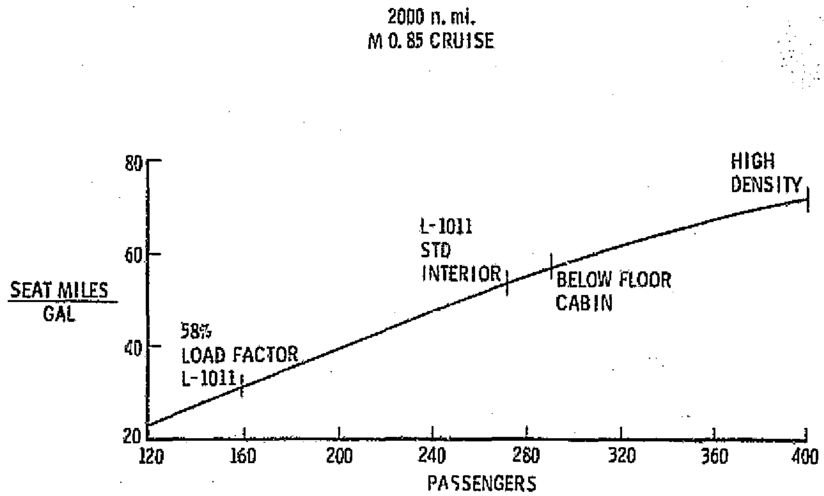


Figure 7.—Effect of passenger/seating density on fuel economy, L-1011

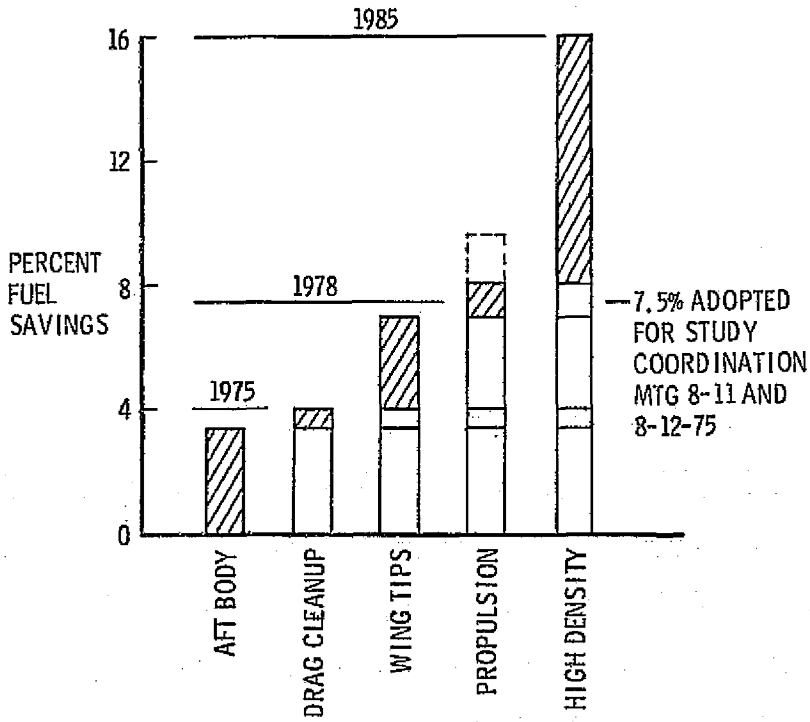


Figure 8.—L-1011 modifications fuel savings summary

TABLE 11.- CALCULATED FUEL CONSUMPTION - L-1011 WITH WING TIP EXTENSIONS

Stage Length n.mi.	Block Fuel Consumption			
	lb	gal / n.mi.	seat-n.mi. / gal	Btu / seat-n.mi.
100	4 962	7.30	37.40	3381
200	8 671	6.38	42.82	2954
400	15 474	5.69	47.98	2636
600	22 235	5.45	50.09	2525
1000	35 008	5.15	53.03	2385
2000	65 373	4.81	56.79	2227
3000	96 421	4.73	57.75	2190
3700	120 000	4.77	57.24	2210
825	29 453	5.25	52.00	2430

TABLE 12.- CALCULATED TOTAL OPERATING COSTS - L-1011 WITH WING TIP EXTENSIONS

Stage Length n.mi.	Block Speed kt	Total DOC		Total IOC	
		$/blk-hr	¢/seat-n.mi.	$/blk-hr	¢/seat-n.mi.
100	233	1745	2.75	5322	8.38
200	296	1630	2.03	3670	4.57
400	349	1497	1.58	2500	2.63
600	376	1437	1.40	1959	1.91
1000	402	1387	1.27	1522	1.39
2000	436	1346	1.13	1170	0.98
3000	451	1336	1.09	1043	0.85
3700	456	1342	1.08	1050	0.84
825	392	1405	1.33	1675	1.56

TABLE 13.- CALCULATED FUEL CONSUMPTION - L-1011 W/15° ENGINE AFTERBODIES

Stage Length n.mi.	Block Fuel Consumption			
	lb	$\frac{\text{gal}}{\text{n.mi.}}$	$\frac{\text{seat-n.mi.}}{\text{gal}}$	$\frac{\text{Btu}}{\text{seat-n.mi.}}$
100	4 911	7.22	37.80	3346
200	8 582	6.31	43.26	2924
400	15 316	5.63	48.48	2609
600	22 007	5.39	50.61	2499
1000	34 649	5.10	53.58	2361
2000	64 702	4.76	57.38	2204
3000	95 432	4.68	58.36	2167
4270	139 500	4.80	56.82	2226
825	29 172	5.20	52.50	2400

TABLE 14.- CALCULATED TOTAL OPERATING COSTS - L-1011 W/15° ENGINE AFTERBODIES

Stage Length n.mi.	Block Speed kt	Total DOC		Total IOC	
		\$/blk-hr	¢/seat-n.mi.	\$/blk-hr	¢/seat-n.mi.
100	233	1794	2.83	5393	8.49
200	296	1656	2.06	3600	4.48
400	394	1505	1.59	2470	2.60
600	376	1434	1.40	1978	1.93
1000	402	1383	1.26	1534	1.40
2000	436	1342	1.13	1177	1.00
3000	451	1332	1.08	1048	0.85
4270	459	1338	1.07	1050	0.84
825	393	1395	1.30	1680	1.57

4. TRISTAR AND ELECTRA FUEL SAVING DERIVATIVES - TASK 4

NASA Specification No. 2-24968, Statement of Work Study Task 1.4.1.4 dated June 3, 1974, regarding analysis of fuel conservation potential of Lockheed existing-production aircraft derivatives suitable for fleet operating service prior to 1980, in effect, specifies analysis of derivatives of the Lockheed L-1011-1 and L-188 Electra aircraft. The Lockheed L-1011-1 is currently in production and will so continue for some time to come; however, the Lockheed L-188 Electra is no longer in production. Because the P-3C, the military version of the L-188 Electra is still in production, it is reasonable to assume that a new derivative L-188 could be produced off the same production line; therefore, a basic P-3C conversion for commercial use was considered which incorporates an interior arrangement and passenger capacity equivalent to the original L-188.

For the purpose of this study, a derivative aircraft is defined as a modified basic production aircraft whose modifications are cost effective and are such that they are not suitable for incorporation as a retrofit for delivered aircraft; i.e., the modifications are suitable only for new production aircraft. Aircraft modifications such as redesigned wings, incorporation of growth engines, and stretched or reduced fuselage lengths were investigated.

It was found that a redesigned wing, supercritical or otherwise, was not cost effective nor compatible with the pre-1980 initial operating capability requirement for any of the Lockheed airplanes. It was determined that their derivatives incorporating reduced or increased passenger-carrying capacities were plausible candidates for aiding air transportation system fuel conservation.

The following pages present the outcome of the Lockheed analyses involving the following derivative aircraft configurations:

1.	L-1011 Long Body	466 000 pounds TOGW	407 Pax
2.	L-1011 Short Body	325 000 pounds TOGW	200 Pax
3.	P-3 Commercial	L-188 Fuselage Length	85 Pax
4.	P-3 Commercial	Stretched Fuselage	105 Pax

Each derivative aircraft is summarily defined and two idealized calculated data tables for each present the fuel consumption and operating cost information. These two tables for each derivative aircraft have been developed using the applicable adopted study ground rules and methods as noted in study Task 1 for the baseline aircraft data development. These data are tabulated for a series of stage lengths including the estimated 1973 CAB average stage length.

4.1 L-1011 Long Body Derivative

Lockheed conducted extensive detailed design studies on stretched fuselage versions of the L-1011 TriStar aircraft during 1973 and 1974. One family of stretched versions incorporated a basic stretch of 360 inches with an airplane TOGW limit of 466 000 pounds. Propulsion options included three different Rolls Royce high-bypass ratio turbofan engines of 42 000, 43 500, and 48 000 pounds sea level static thrust each. Passenger capacities ranged from 407 to 500. One of these L-1011 derivatives was selected for evaluation in this study.

The L-1011 Long Body derivative considered in this study incorporates the addition of constant diameter barrel sections in the fuselage fore and aft of the wing. The engines are changed from the Rolls Royce RB.211-22B to the 48 000 pound static sea level thrust RB.211-524. Extending the fuselage increases the passenger capacity from 273 to 407. The aircraft takeoff gross weight is increased from 430 000 pounds to 466 000 pounds. The wing incidence is increased by 2° 40' to maintain the same after-body rotation ground clearance (main landing gear unchanged).

The L-1011 Long Body aircraft general arrangement is shown in Figure 9. Table 15 is a summary of the aircraft characteristics. Table 16 describes the aircraft basic interior arrangement. The aircraft weight summary for the L-1011 Long Body derivative aircraft is presented in Table 17.

Table 18 presents the L-1011 Long Body derivative airplane total block fuel consumption for various stage lengths. Table 19 presents airplane total operating costs and block speeds for various stage lengths.

4.2 L-1011 Short Body Derivative

The initial basic engineering and economic data for this version of the TriStar were developed under Lockheed 1974 IRAD studies and adapted to this study. The results of the 1974 IRAD work are documented in Lockheed Report LR 27019, dated 10 January 1975, entitled L-1011 Short Range Derivative Study - 1974, (Lockheed Private Data). This IRAD study investigated two and three-engined shortened-fuselage derivatives of the L-1011-1 designed for the same short range mission. The basic aircraft design requirements utilized are shown in Table 20. A three-engined short-bodied L-1011 aircraft version was developed which utilized the Rolls Royce RB.211-22B engine operating at a seven percent lower thrust level than the engines of the basic L-1011 configuration for purposes of improved operating economy. A twin-engined short-bodied L-1011 aircraft version was developed which utilized the Rolls Royce RB.211-524 engine. The superiority of the tri-jet short-body configuration was established in the study, primarily because of takeoff performance.

Table 21 presents a listing of the changes in the basic L-1011-1 aircraft required to obtain the L-1011 three-engined short-bodied derivative selected for evaluation in this study. The resulting short-bodied L-1011 aircraft basic weights are also noted. Figure 10 presents the general arrangement of the short body airplane and indicates the overall length comparison with the baseline L-1011-1 TriStar.

Table 22 presents the L-1011 Short Body derivative aircraft total block fuel consumption for various stage lengths. Table 23 presents airplane total operating costs and block speeds for various stage lengths.

4.3 P-3 Commercial-85 Pax and 105 Pax

The U.S. Navy land-based antisubmarine patrol P-3 aircraft was derived from the Lockheed L-188 Electra turboprop commercial airplane whose various interior arrangements accommodated 85 to 97 passengers. The Electra basic fuselage length was reduced by 88 inches forward of the wing for the conversion to the P-3. The current production P-3 ASW aircraft is designated P-3C. Figure 11 depicts the general arrangement of the P-3C aircraft.

This portion of the derivative aircraft analysis effort, under study Task 4 investigates the conversion of the P-3C airplane into a commercial transport. The major premise is that the conversion will be accomplished with minimum modification. The modifications and other cost factors used in the derivation of the direct and indirect expenses are outlined in the following. Two conversions are considered: 1) converting the P-3C back to the original L-188 configuration, and 2) stretching the fuselage to increase the capacity from 85 passengers to 105 passengers.

<u>Deletions and additions to P-3C airframe</u>

- Deletions
  - Wiring to bomb bay, avionics wing stores, and armament
  - Sonobuoy chutes
  - MAD boom
  - Flight station exit
  - ASW avionics racks and equipment
  - Window for periscope sextant
  - Water injection system
  - ASW antennas.
- Additions
  - 88 inch fuselage plug forward of the wing for 85 passenger configuration, and an additional plug for 105 passenger configuration also forward of the wing.
  - Passenger door and self-contained stairs
  - Passenger windows
  - Passenger accommodations
  - Convert bomb bay into baggage hold
  - Move electrical load center.

Tables 24 and 25 present the calculated fuel consumption and total operating costs respectively for the 85 passenger P-3 commercial aircraft for various stage lengths. The same data for the 105 passenger P-3 commercial aircraft is presented in Tables 26 and 27.

The commercial P-3 performs well in terms of fuel consumption but is high in DOC due to the high purchase cost in terms of passengers carried.

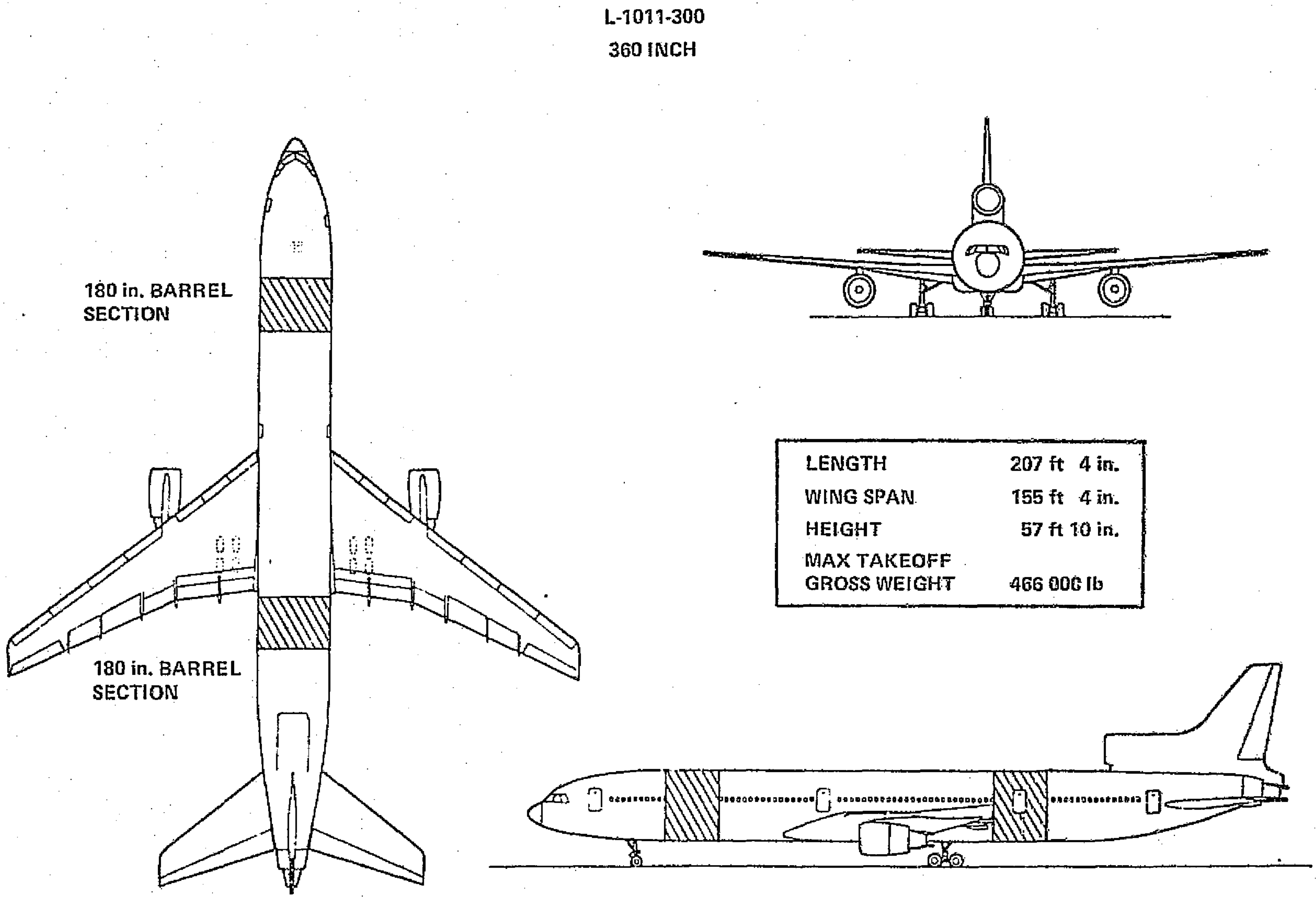


Figure 9.—L-1011 long body derivative general arrangement

- SHORT RANGE 3 ENG TRANSPORT L-1011- DERIVATIVE
- BODY LENGTH 21' 8" LESS THAN L-1011-1

	WING	H/TAIL	V/TAIL
AREA sq ft	3456	1282	550
ASPECT RATIO	6.95	4	1.6
TAPER RATIO	0.30	0.33	0.30
SPAN	155 ft	71 ft 7 in.	29 ft 8 in.
ROOT CHORD	412 in.	323 in.	342 in.
TIP CHORD	123 in.	107 in.	102.6 in.
MAC	293.5 in.	233 in.	243.8 in.
SWEEP @ 1/4C	35°	35°	35°

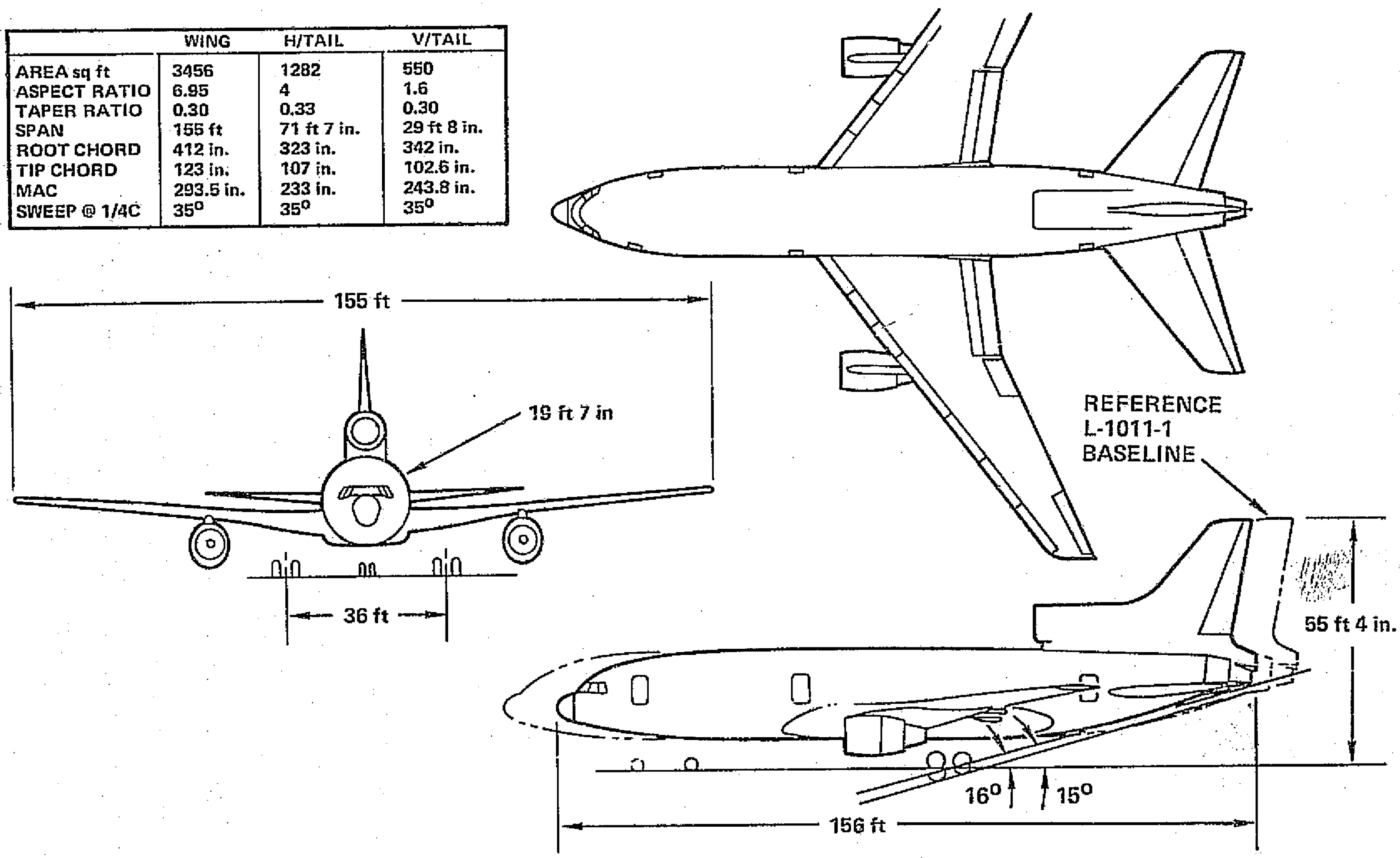


Figure 10.—L-1011 short body derivative general arrangement

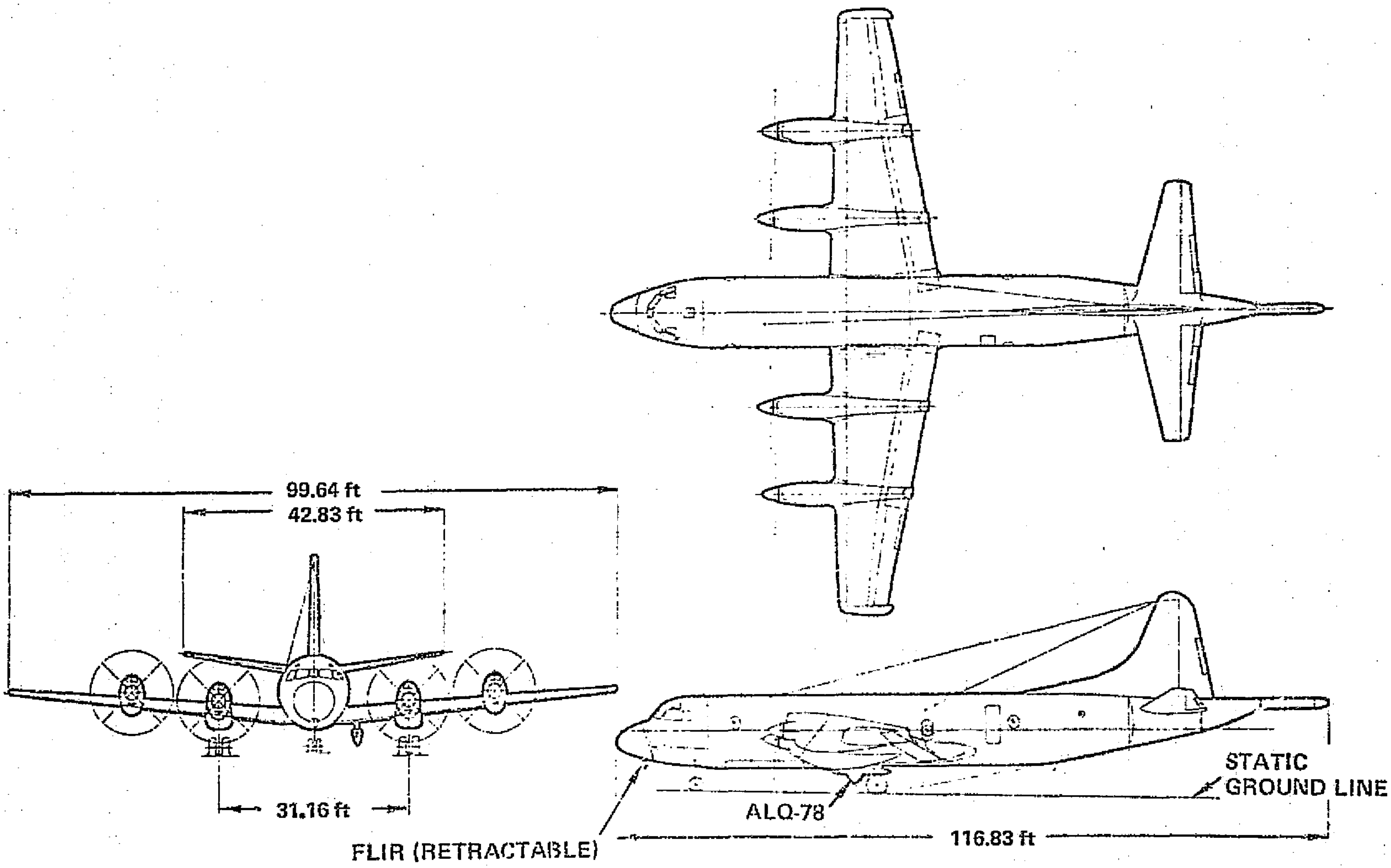


Figure 11.—P-3C general arrangement

TABLE 15.- L-1011 LONG BODY DERIVATIVE CHARACTERISTICS SUMMARY - L-1011-300 - RB.211-524 ENGINE

Configuration	360-2
Engine Thrust - SLS, 84 °F	48 000
Design Weights	
Takeoff	466 000
Landing	393 000
Max. Zero Fuel	363 000
Operating Empty	274 984
Wt. Limit Payload	88 016
Space Limit Payload*	90 170
Pass. - Cargo Accommodations	
Number of Passengers	407
Galley Location	Lower
LD-3 Containers	14
Performance	
Range, Full Pass. + Bag. - n.mi.*	1850
TOFL, SL Std. + 13.9 °C - ft	8450
LFL at Design Landing Wt. - ft	6070

*Based on 150 lb/passenger + baggage and cargo at 10 lb/cu ft

TABLE 16.- L-1011 LONG BODY DERIVATIVE INTERIOR ARRANGEMENT - L-1011-300

	10/90 FC/Economy
Galley Location	Lower
Y Seating (Abreast)	9
FC Seating (Abreast)	6
Food Service	1 Meal
Passenger (Total)	407
FC	46
Y	317
Lower Deck	44
Seat Pitch	
FC	38
Y	33/34
Lower Deck	33/34
Config. Number	360-2

TABLE 17.- L-1011 LONG BODY DERIVATIVE WEIGHT SUMMARY - L-1011-300

	Config. 360-2
MEW L-1011-1	224 807
Design Weights (430/440K)	748
Design Weights (466/440K)	3491
Fuselage Barrel Structure (30 Foot Extension)	6953
Structural Changes (Wing Incidence 2°40')	1707
Fuselage Structure Between Plugs	2490
Passenger Door Main Cabin (Type A ILO Type 2)	200
Propulsion (Noise Suppression)	500
Below Deck Passenger Compartment	9848
Delete Below Deck Galley	NA
Main Cabin Interior (30 Foot Extension)	5124
Systems (30 Foot Extension)	1337
Mid Cargo Compartment (Class C ILO Class D)	360
Forward Cargo Compartment (Delete C-1 Cargo Door)	-662
MEW L-1011-300 (30-Foot Extension)	256 903
Unusable Fuel	206
Operating Equipment	16 874
OEW L-1011-300 (30-Foot Extension)*	273 983
Space Limit Payload**	90 170
Weight Limit Payload	89 017

*RB211-22F Engines, add 1001 lb for RB211-524 engines

**Space limit payload = 150 lb/Pax + baggage and cargo at 10 lb/ft^3

TABLE 18.- CALCULATED FUEL CONSUMPTION - L-1011 LONG BODY -524 ENGINES

Stage Length n.mi.	Block Fuel Consumption			
	lb	gal / n.mi.	seat-n.mi. / gal	Btu / seat-n.mi.
100	4 911	7.22	56.37	2244
200	8 840	6.50	61.62	2020
400	16 599	6.10	66.69	1896
600	24 064	5.90	69.00	1833
1000	38 306	5.63	72.25	1751
2000	75 138	5.52	73.67	1717
3000	113 935	5.59	72.87	1736
3275	125 500	5.62	71.81	1751
1170	44 315	5.57	73.00	1750

TABLE 19.- CALCULATED TOTAL OPERATING COSTS - L-1011 LONG BODY -524 ENGINES

Stage Length n.mi.	Block Speed kt	Total DOC		Total IOC	
		\$/blk-hr	¢/seat-n.mi.	\$/blk-hr	¢/seat-n.mi.
100	208	1910	2.25	6371	7.51
200	282	1803	1.57	4750	4.14
400	333	1675	1.24	3320	2.45
600	375	1615	1.06	2641	1.73
1000	408	1569	0.94	2094	1.26
2000	439	1535	0.86	1620	0.91
3000	451	1531	0.83	1449	0.79
3275	452	1532	0.83	1420	0.77
1170	415	1560	0.92	2000	1.18

TABLE 20.- SUMMARY SHORT RANGE L-1011 DESIGN REQUIREMENTS - 1974

Characteristics

- 200 Pax, 20F/180Y (L-1011-1 Comfort Standards)
- 5000 lb Maximum Cargo Capacity
- Minimum Service Above Deck Galley (One Meal Capacity)
- Seat Dimensions — Equivalent to L-1011-1 for 8 and 9 Abreast Seating
- Self Sufficiency — L-1011-1 Minus 10% GSE Value per Station
- Community Noise — FAR 36 Minus 8 EPNdB Takeoff and Minus 5 EPNdB Approach
- Fly-Thru-Capability — 1000 n.mi. Range at Full Pax Load after First Stop (Objective)

Performance

- Optimum Cruise Speed — 0.78 Mach
- Field Length — 7000 ft at S.L. and 84 °F for Full Payload Range Mission. A Range of 500 n.mi. Achievable with a TOFL of 6000 ft
- Range with Full Pax Load Plus 5000 lb Cargo — 1500 n.mi. (Domestic Reserves)
- Fuel Efficiency — Equivalent to L-1011 (200 Pax) Minus 10% in Pounds/Seat-Nautical Mile at 500 n.mi. Range

Economics

- Airplane DOC Maximum — 80% of L-1011-1 at 500 n.mi. (Objective 75%)
- Seat-Nautical Mile DOC — Equal to L-1011-1 at 500 n.mi. (Mixed Class and All-Coach Seating Standards)
- Fly-Away Price — In Proportion to L-1011-1 Fly-Away Price to Meet DOC Ratios as Above and Allow Program Profitability Based on a Low Risk Market of Approximately 325 Airplanes

Availability

- FAA Certification — First Quarter 1979

Suggested Design Limitation

- Simplified 2 and 3 Engine L-1011-1 Versions (Low Development Cost)

TABLE 21.- L-1011-1 AIRCRAFT MODIFICATIONS REQUIRED FOR SHORT BODY DERIVATIVE

(L-1011-Short Range Derivative Study - 1974)

L-1011-SR Definition

Selected Candidate Changes to the Basic L-1011-1 Airplane Which Define the Short Range Derivative Aircraft.

- Minimum Modification
- 3 RB.211-22B Engines, Derated 7%
- Shorten Fuselage 260 in.
  - 150 in. from Fwd End of Sec 3
  - 40 in. from Aft End of Sec 5
  - 70 in. from Fwd End of Sec 6
- Remove P4, Galley and C2 Doors
- Remove Below Deck Galley, Lifts and Provisions
- Remove 1 Aft Lavatory and Associated Systems
- Remove 1 ECS Pack and Associated Ducting
- Remove Aft Cargo System
- Redesign MLG Fairing - Fwd of FS901
  - Aft of FS1455
- Remove Outboard Flaps, Outboard Spoilers and Associated Systems - Replace with Fixed Structure
- Reduce Wing Skin and Stringer Gages
- Reduce Horizontal Stabilizer Skin Plank Gages
- Delete Food Carts

The Following Aircraft Weights are for the L-1011 Short Body Aircraft

TOGW	325 000 lb
ZFW	275 000 lb
OEW	210 154 lb

TABLE 22.- CALCULATED FUEL CONSUMPTION - L-1011 SHORT BODY

Stage Length n.mi.	Block Fuel Consumption			
	lb	gal / n.mi.	seat-n.mi. / gal	Btu / seat-n.mi.
100	4 518	6.64	30.12	4199
200	7 858	5.78	34.60	3655
400	14 340	5.27	37.95	3333
600	20 332	4.98	40.16	3149
1000	31 430	4.62	43.29	2922
1500	45 574	4.47	44.74	2827
2000	59 128	4.35	45.98	2751
2600	76 612	4.33	46.19	2738
600	20 332	4.98	40.16	3149

TABLE 23.- CALCULATED TOTAL OPERATING COSTS - L-1011 SHORT BODY

Stage Length n.mi.	Block Speed kt	Total DOC		Total IOC	
		$/blk-hr	¢/seat-n.mi.	$/blk-hr	¢/seat-n.mi.
100	233	1565	3.37	4154	8.93
200	294	1460	2.48	2720	4.62
400	357	1328	1.86	1910	2.67
600	380	1268	1.67	1531	2.02
1000	413	1225	1.48	1197	1.45
1500	432	1202	1.39	1008	1.17
2000	442	1189	1.34	905	1.02
2600	448	1180	1.32	830	0.93
600	380	1268	1.67	1531	2.02

TABLE 24.- CALCULATED FUEL CONSUMPTION - P-3 COMMERCIAL 85 PAX

Stage Length n.mi.	Block Fuel Consumption			
	lb	gal/n.mi.	seat-n.mi./gal	Btu/seat-n.mi.
100	2 500	3.68	23.10	5475
200	3 800	2.79	30.47	4151
400	6 500	2.39	35.56	3557
600	9 000	2.21	38.46	3289
1000	14 000	2.06	41.26	3065
1500	20 300	1.99	42.71	2961
2000	26 800	1.97	43.15	2931
2295	30 500	1.95	43.49	2908
300	5 182	2.54	33.50	3775

TABLE 25.- CALCULATED TOTAL OPERATING COSTS - P-3 COMMERCIAL 85 PAX

Stage Length n.mi.	Block Speed kt	Total DOC		Total IOC	
		$/blk-hr	¢/seat-n.mi.	$/blk-hr	¢/seat-n.mi.
100	170	861	5.98	1259	8.74
200	222	767	4.06	907	4.80
400	268	699	3.06	644	2.82
600	294	670	2.68	530	2.12
1000	314	643	2.41	432	1.62
1500	322	627	2.29	373	1.36
2000	327	618	2.22	341	1.23
2295	329	612	2.19	328	1.17
300	247	725	3.41	745	3.51

TABLE 26.- CALCULATED FUEL CONSUMPTION - P-3 COMMERCIAL 105 PAX

Stage Length n.mi.	Block Fuel Consumption			
	lb	gal/n.mi.	seat-n.mi./gal	Btu/seat-n.mi.
100	2 669	3.92	26.79	4728
200	4 057	2.98	35.18	3593
400	6 939	2.55	41.18	3073
600	9 608	2.36	44.59	2837
1000	14 946	2.20	47.77	2648
1500	21 672	2.12	49.42	2559
2000	28 612	2.10	49.90	2534
2145	30 700	2.10	49.88	2535
300	5 549	2.72	39.00	3275

TABLE 27.- CALCULATED TOTAL OPERATING COSTS - P-3 COMMERCIAL 105 PAX

Stage Length n.mi.	Block Speed kt	Total DOC		Total IOC	
		$/blk-hr	¢/seat-n.mi.	$/blk-hr	¢/seat-n.mi.
100	170	896	5.03	1451	8.15
200	222	797	3.42	1044	4.47
400	268	726	2.58	738	2.62
600	294	697	2.26	600	1.94
1000	314	667	2.02	493	1.49
1500	322	650	1.92	425	1.26
2000	327	642	1.87	387	1.13
2145	328	640	1.86	382	1.11
300	250	750	2.86	855	3.26

5. NEW NEAR-TERM (1980) FUEL SAVING AIRCRAFT - TASK 5

In addition to the methods studied to reduce the fuel consumption of the air transport fleet in the previous study tasks, a series of new fuel conserving aircraft was parametrically designed and evaluated. The purpose of this task was to evaluate the fuel savings to be realized if new near-term aircraft were designed from the outset with the current high and possibly higher future fuel cost environment as a design criterion. Near-term for purposes of this task was defined as 1980 initial operations capability.

The design mission requirements for the new aircraft of this task were defined by NASA in the proposal request. Three payload/range classes, with airplanes designed to four particular criteria in each class, were included. All of these aircraft were to incorporate turbofan engines, and in addition a turboprop aircraft was to be studied for one of the payload/ranges. The three size classes were a 200 passenger aircraft for a 1500 nautical mile design mission, and both a 200 and 400 passenger aircraft for a 3000 nautical mile mission. In designing aircraft for each of these missions, minimum direct operating cost as well as minimum fuel design criteria were utilized. The minimum direct operating cost criterion was further divided by the specification of three fuel costs: 15, 30, and 60 cents per gallon. The 200 passenger, 1500 nautical mile payload/range was stipulated for evaluation of the turboprop aircraft. Table 28 summarizes this matrix of payload/range and design criteria.

5.1 Turbofan Aircraft Designs

As a first step in the parametric evaluation of the Table 28 designs, preliminary sizing and conceptual design studies were performed. These studies established the basic configurations, sizes, and weights for the three classes of airplanes to be considered. Preliminary configuration drawings were then prepared and used as a basis for assessing the drag, propulsion, stability and control requirements, and the structural and weight relationships as required for each of the aircraft.

It was projected that for introduction in 1980 the most likely candidate airplanes in the payload/range classes being considered would incorporate widebody fuselages and the current high-bypass ratio engines or derivatives of same. The L-1011 fuselage diameter was chosen with four conventional wing/pylon mounted high-bypass ratio turbofan engines being selected. Aircraft systems were chosen compatible with L-1011 design practice.

The 1980 aircraft service introduction was a major factor in determining the fuel efficient technologies to be incorporated. A supercritical wing and limited use of advanced composites in cost effective secondary structure were selected as offering the most potential for incorporation in an airplane designed for 1980 service. Active flight controls and composite primary structure were eliminated as viable candidate technologies for this time period.

Aerodynamic, weight, and cost data representative of these advanced technologies were generated in parametric form. Scalable engine data were generated in deck form based on the cycle performance and weight of the Rolls-Royce RB.211 high-bypass ratio turbofan engine. With these component characteristics defined in parametric form, parametric aircraft studies were conducted using the Lockheed Advanced System Synthesis and Evaluation Technique (ASSET) computer program. This program was used to size preliminary design airplanes in each of the mission classes for a range of Mach numbers, wing aerodynamic parameters, wing, and thrust loadings. This design matrix is shown in Table 29; repeated for each of the three payload/range classes, 12 288 parametric airplane designs result. The selection of this matrix was based on extensive in-house preliminary studies; this accounts for the lower limit established on sweep angle for example where it was found that for the range of thickness ratios considered, only very small additional fuel and operating cost benefits were achieved with further reductions in sweep angle.

The automatic plotting capability of the ASSET program was used to generate carpet plots of takeoff gross weight, block fuel, and direct operating cost for each of the three fuel costs. The full range of wing aspect and thickness ratios shown in Table 29 were thereby combined for each of the selected wing and thrust loadings. The minimum takeoff gross weight, minimum block fuel, and minimum direct operating costs were selected from the autoplots and tabulated along with the appropriate wing geometry (aspect and thickness ratios). Summary cross-plots of the minimum values were then prepared over the range of thrust and wing loadings at each Mach number. These cross plots allow incorporation of field length constraint lines.

Use of the tabulated minimum value data obtained from the autoplots and the cross plots allowed the construction of curves for the variation of wing geometry with Mach number for each of the payload/range combinations. An example is shown in Figure 12. In performing this step of the procedure, the minimum direct operating cost and minimum fuel criteria were used and were modified when necessary by the field length constraints. Note that in Figure 12, one curve represents all wing loadings since the geometry was found to be insignificantly affected over the range of wing loadings considered.

Final summary plots showing the variation of takeoff gross weight, block fuel, and direct operating cost with Mach number were then constructed (examples shown in Figures 13, 14, and 15). This was accomplished by again referring to the computer plotted data and the summary plots as shown in Figure 12. The final Mach numbers were selected from the data typified by Figures 13 through 15.

Tables 30 through 33 summarize the characteristics of the final selected design point airplanes for the minimum DOC and minimum fuel criteria. These tables were constructed from an additional set of ASSET computer output for each design-point airplane which was run at the specific wing geometry and cruise Mach number selected as discussed above. A complete set of geometry, weight, performance, and cost data was therefore available for each of the final selected airplanes.

Typical tabular data in the format specified for the UTRC study (Reference 1) are presented as Tables 34 through 37. For that study the 15 cent fuel designs were eliminated so that the data were developed for the 30 and 60 cent fuel designs and for the minimum fuel design. These data are tabulated for a series of stage lengths including one predicted to be the average CAB stage length assuming these aircraft were in service. Fuel consumption is shown in terms of total block fuel and on both an airplane-nautical mile and a seat-nautical mile basis. The seat-nautical mile figures are further subdivided into units of seat-nautical miles per gallon and Btu's per seat-nautical mile. Total direct and indirect operating costs are tabulated assuming fuel prices of 15, 30, and 60 cents per gallon. These total cost figures are shown in units of dollars per block hour with the corresponding block speeds indicated at each stage length and are also shown in units of cents per available seat-nautical mile.

5.2 Turboprop Aircraft Designs

The 200 passenger/1500 nautical mile payload/range was stipulated for the turboprop design. In this aircraft size class, the turbofan parametric study airplanes optimized at cruise Mach values of 0.75 or higher. This indicates that the block-time factor is still a powerful one when considering direct operating cost as a design criterion even at elevated fuel prices. It was also shown that for aircraft powered by the turbofan engines investigated in this study, the high fuel cost/minimum direct operating cost design does not differ drastically from one designed strictly from a minimum fuel standpoint in terms of the design Mach number.

These high cruise speeds, considered in the context of the 1980 operating time period, complicate the consideration of turboprop designs. Current propeller designs limit the design speed of a turboprop powered aircraft to approximately Mach 0.65, a speed that was judged to be unacceptable from the standpoint of compatibility with current aircraft that will still be in the fleet in 1980. Advanced propellers such as the Hamilton Standard Prop-Fan which would allow operation at speeds up to Mach 0.8 or better will not be available until sometime after the specified 1980 aircraft service introduction date.

The turboshaft engine for use in the 1980 time period was an additional factor for consideration. While available turboshaft engines offer specific fuel consumption benefits comparable to even the current high-bypass turbofan engines at competitive cruise speeds and even larger benefits at reduced cruise speeds, none offer sufficient power for the size aircraft envisioned.

With these considerations as a basis, it was decided that for purposes of this task some relaxation of the ground rules would be acceptable. It was, therefore, assumed that a current turboshaft engine could be made available in an appropriate size class for incorporation on an aircraft designed to cruise at lower Mach numbers with conventional propellers. At the other end of the speed spectrum an aircraft incorporating a new design engine and propeller was examined.

While several designs in each of these classifications were examined, typical examples are discussed here. The first of these, illustrated in the general arrangement of Figure 16 is a four engined airplane designed to cruise at Mach 0.65 using a conventional four bladed propeller and an uprated version of the Rolls-Royce Tyne powerplant. A wide-body fuselage was used here for compatibility with the other aircraft considered in this task. The wing sweep has been reduced to a value of 15 degrees, sufficient for the lowered cruise speed. The high aspect ratio wing that was found to be optimum for the turbofan airplanes is retained. A design such as this offers seat-mile per gallon figures approximately 25 percent better than the new near-term turbofan airplane. While these improvements are significant, the cruise speed incompatibility of this type of design could possibly out-weigh the fuel savings.

Preliminary design turboprop airplanes designed to cruise at Mach 0.8 are typified by Figures 17 and 18. These airplanes were studied and performance data obtained using the available information on the Hamilton Standard Prop-Fan propeller concept and the Pratt and Whitney STS476 study turboshaft engine. While these data were preliminary in nature at the time of this study, it was felt that an indication of the performance levels attainable would at least help to define the potential of an advanced turboprop aircraft.

It was found again that the seat-mile per gallon levels attainable with the higher speed turboprops were sufficiently improved over the turbofans to call for additional study.

As noted previously, the time period originally specified for introduction of the near-term aircraft placed limitations on the study of the turboprop powered aircraft. The large fuel savings identified in the preliminary design turboprops, however, led to modifications of both of the airframe manufacturer's contracts. A more detailed design of a high speed turboprop and comparison with an equal technology turbofan aircraft was specified in the Lockheed study while McDonnell Douglas was assigned the task of studying a turboprop in the DC-9 size class. Details of the follow-on turboprop study are included in Section 7, Task 7 of this report.

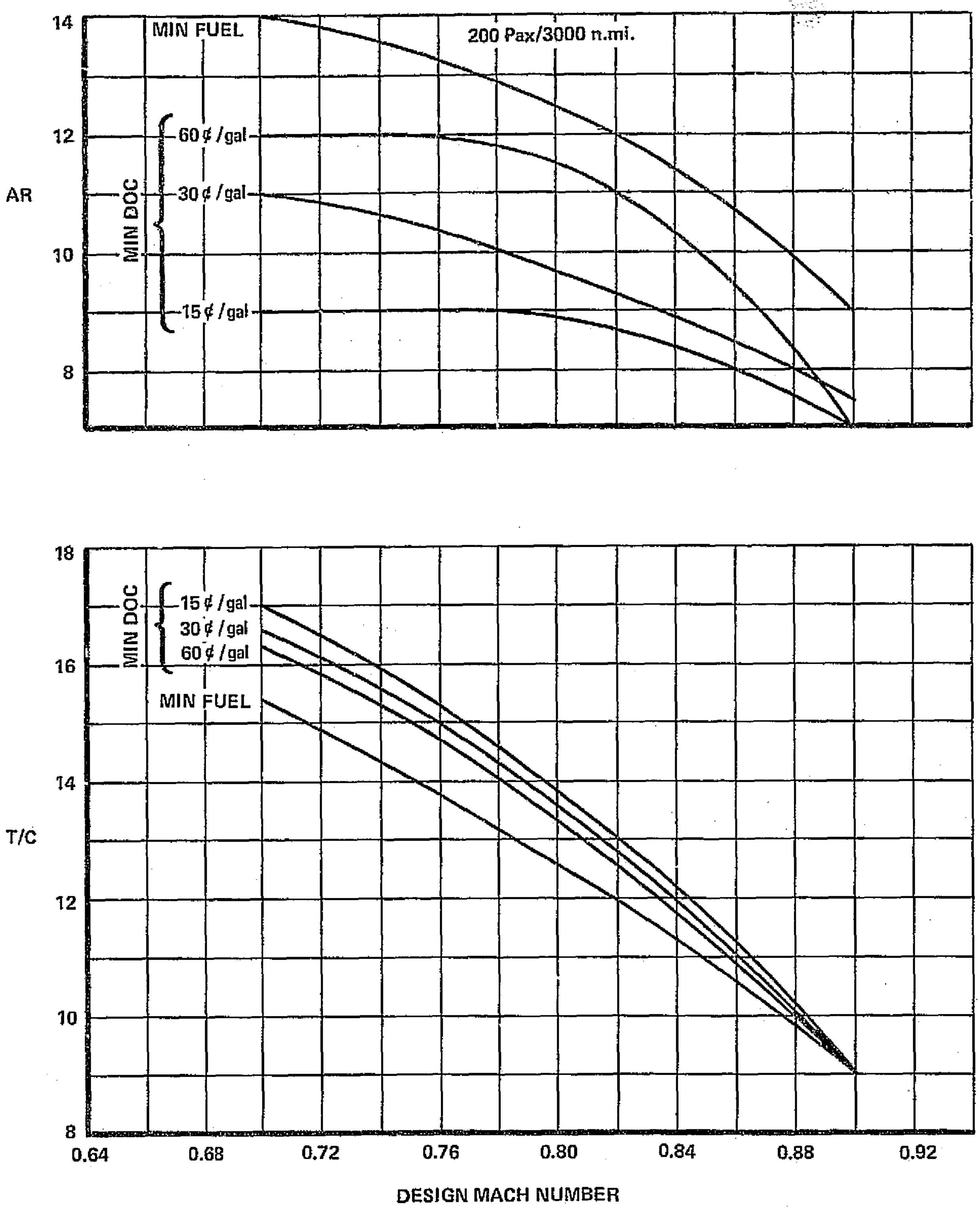


Figure 12.-Effect of design Mach number on wing geometry

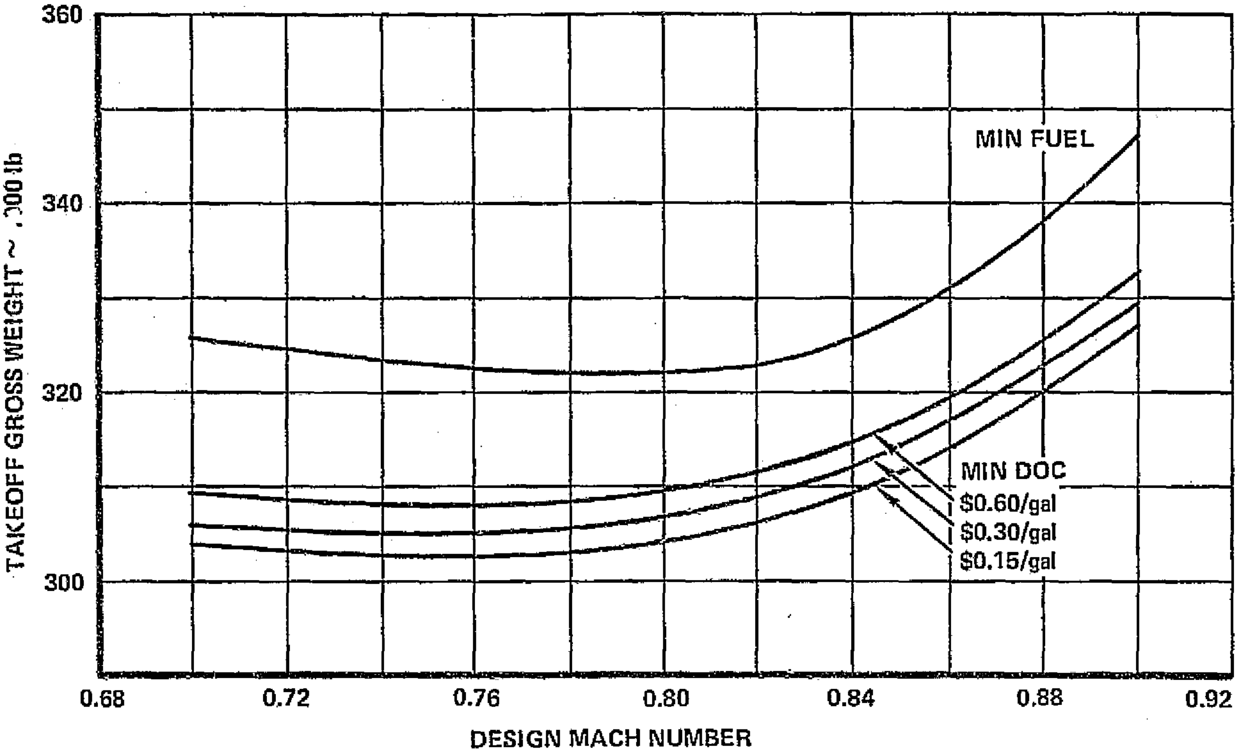


Figure 13.—Effect of design Mach number on takeoff gross weight

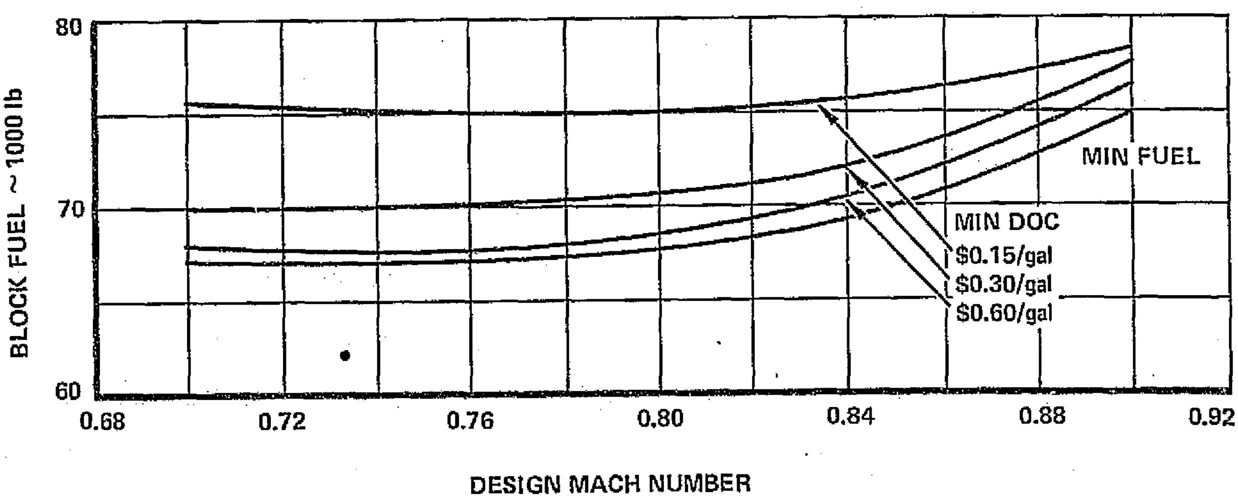


Figure 14.—Effect of design Mach number on block fuel

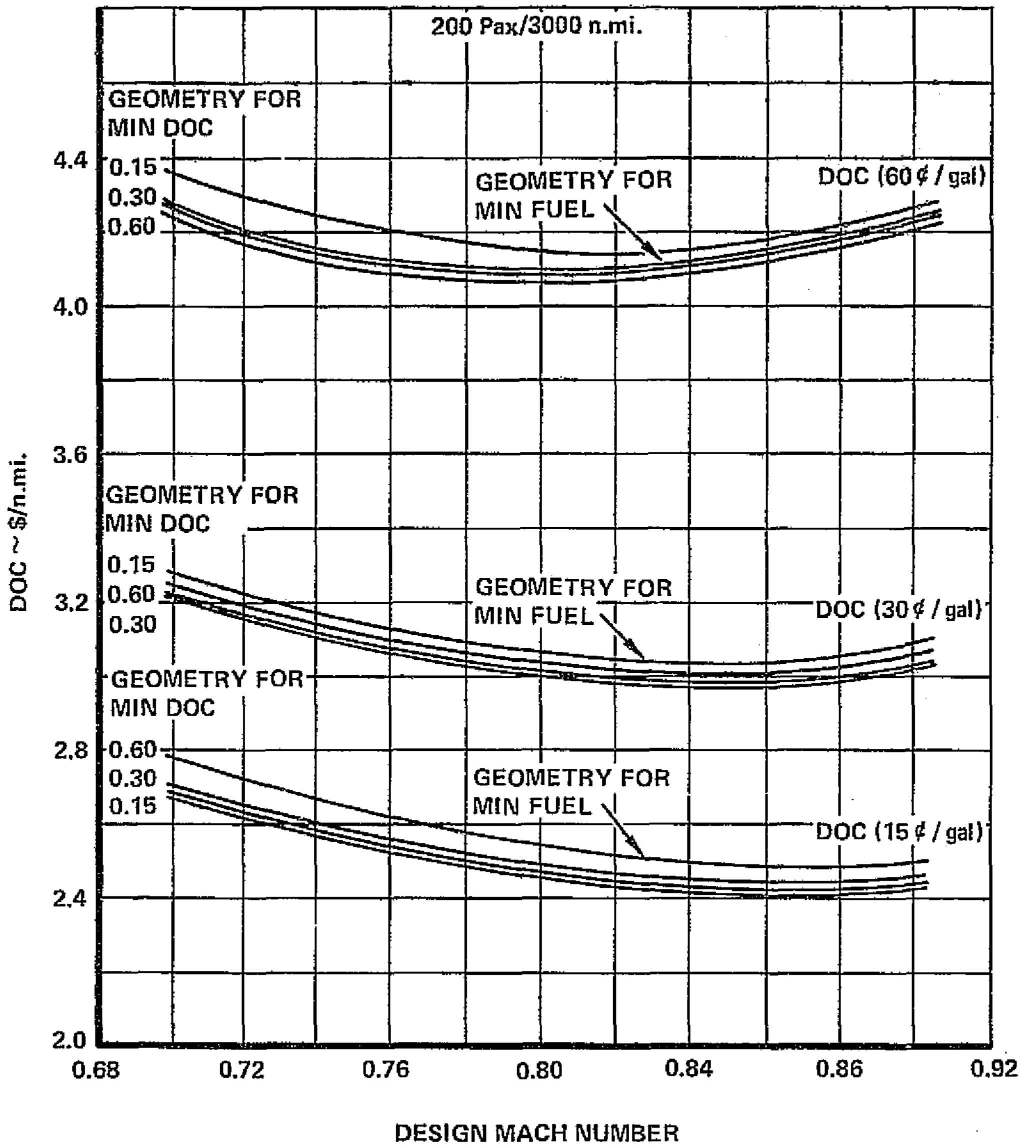
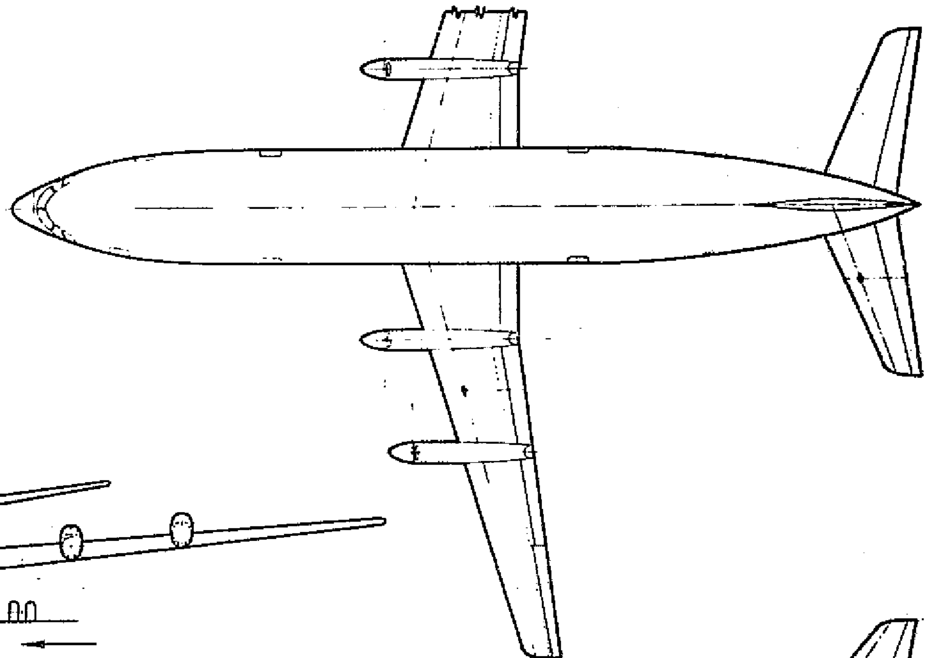
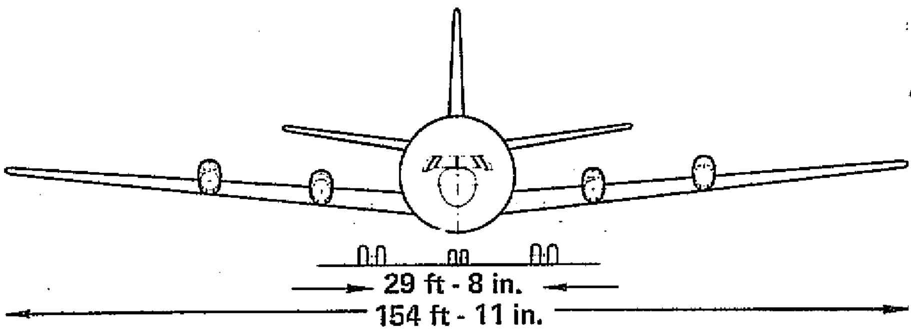


Figure 15.—Effect of design Mach number on direct operating cost

CHARACTERISTICS	WING	HORIZ	VERT
AREA (ft^2)	2000	600	236
ASPECT RATIO	12	6	1.6
SPAN (ft)	154.9	60	19.43
ROOT CHORD (in.)	238.4	171.5	224.2
TIP CHORD (in.)	71.5	68.5	67.3
TAPER RATIO	0.30	0.40	0.30
MAC (in.)	169	125	153
SWEEP C/4 (deg)	15	20	35
T/C ROOT (%)	18	12	12
T/C TIP (%)	14	12	12





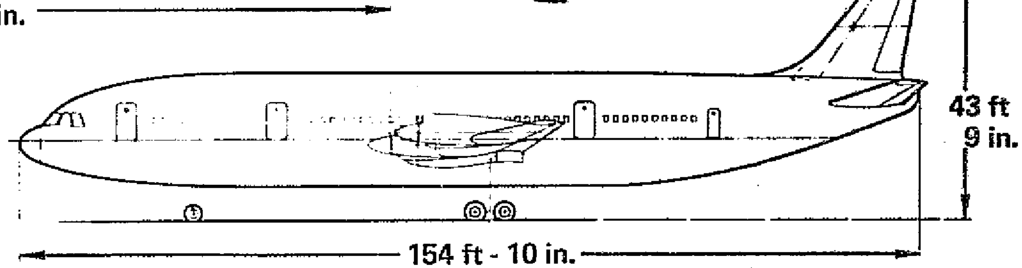


Figure 16.—M 0.65 turboprop transport

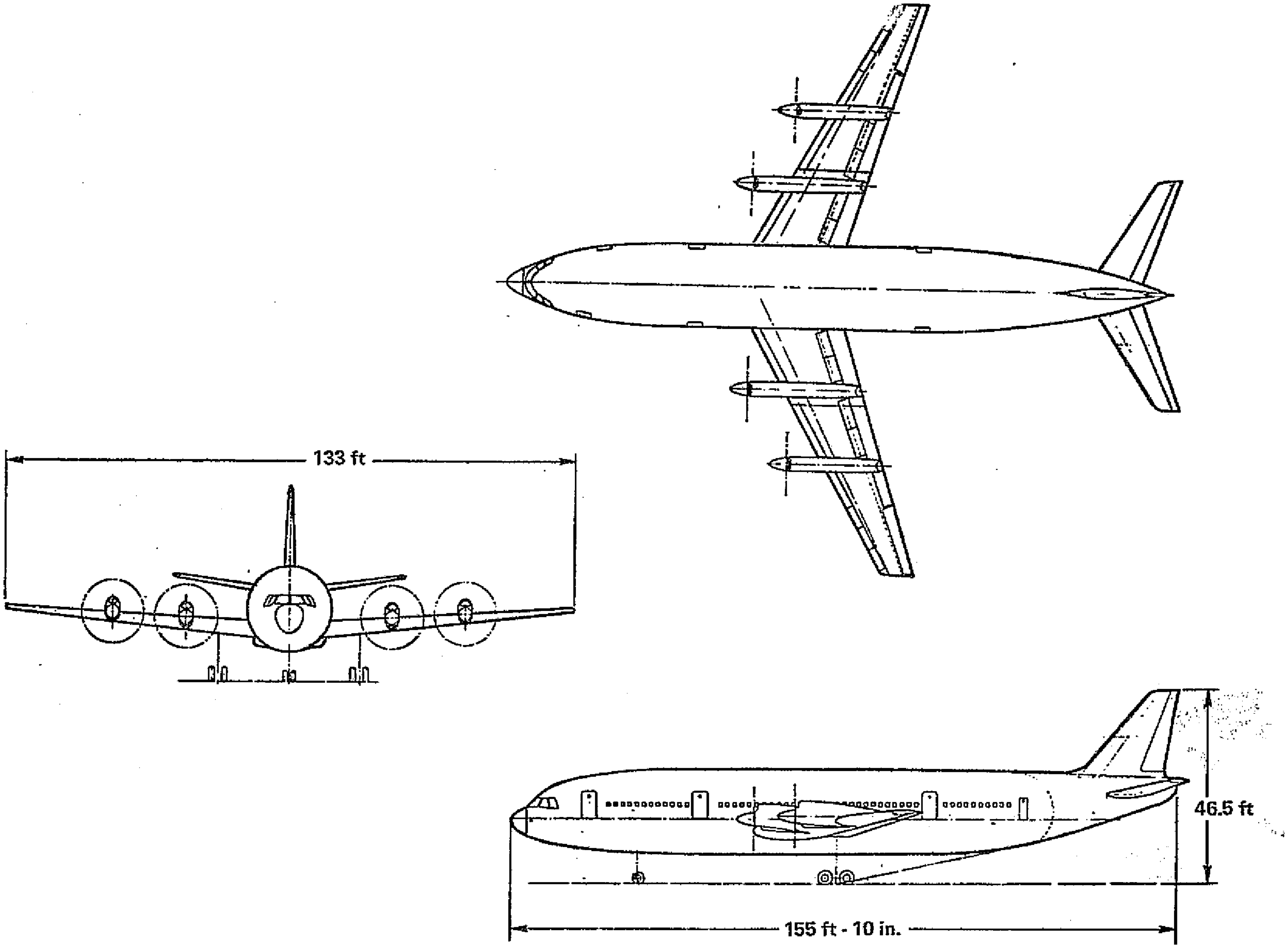


Figure 17.—M 0.80 turboprop concept - 4 engine

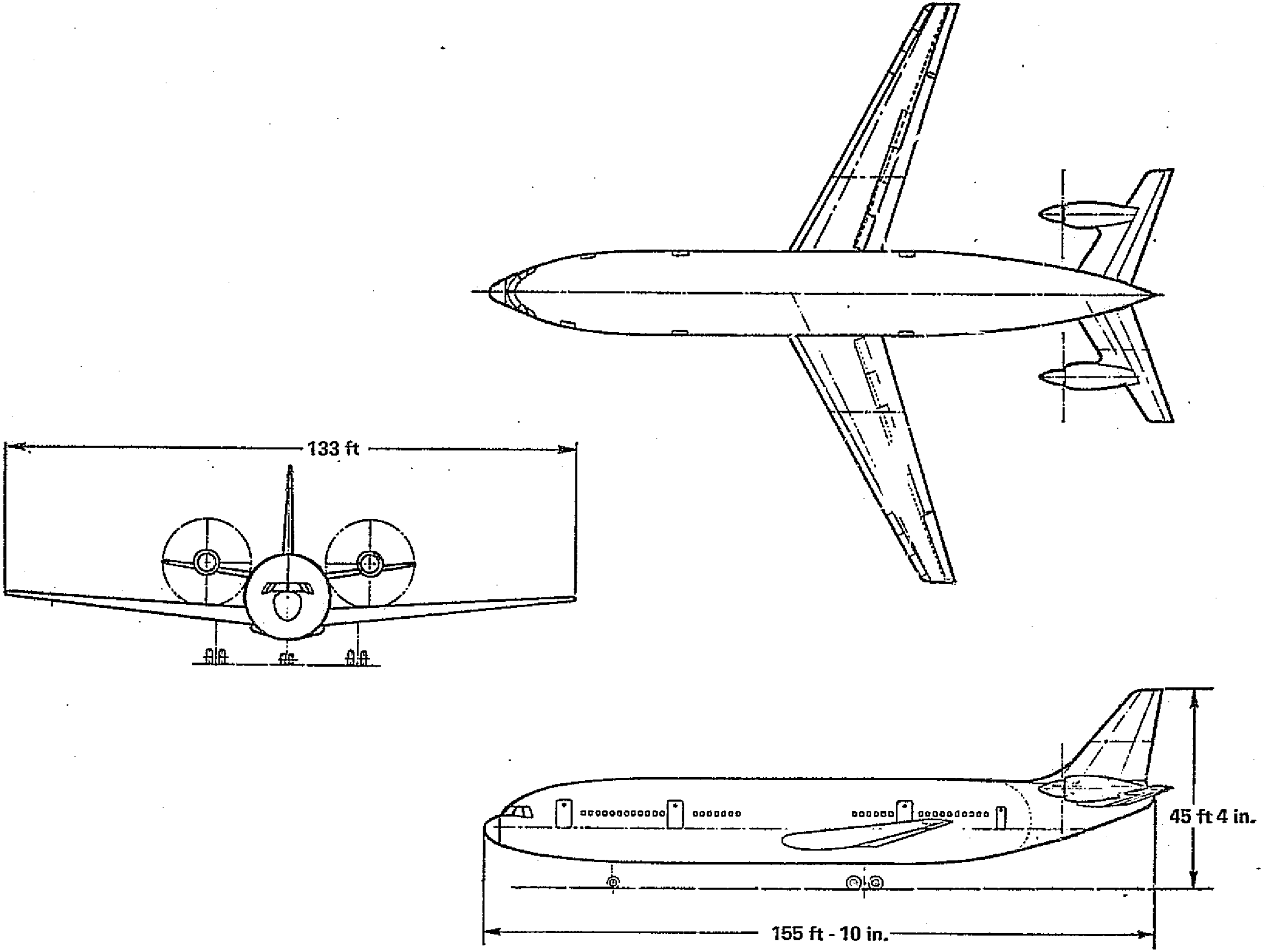


Figure 18.—M 0.80 turboprop concept - 2 engine

TABLE 28.- PAYLOAD/RANGE AND DESIGN CRITERIA

Size			
Passengers	200	200	400
Range (n.mi.)	1500	3000	3000
Design Criteria			
Minimum DOC (15¢/gal Fuel)	X	X	X
Minimum DOC (30¢/gal Fuel)	X	X	X
Minimum DOC (60¢/gal Fuel)	X	X	X
Minimum Fuel	X	X	X
Powerplants			
Turbofan	X	X	X
Turboprop	X		

TABLE 29.- NEW NEAR-TERM AIRCRAFT PARAMETRIC DESIGN MATRIX

M	0.70				0.75				0.82				0.90			
Sweep Angle	25	30	35	40	25	30	35	40	25	30	35	40	25	30	35	40
t/c	9	12	14	16	9	12	14	16	9	12	14	16	7	9	11	13
AR	7	9	12	14	7	9	12	14	7	9	12	14	5	7	9	12
W/S	110	120	125	130	110	120	125	130	110	120	125	130	110	120	125	130
T/W	.22	.26	.30	.32	.22	.26	.30	.32	.22	.26	.30	.32	.26	.28	.30	.34

TABLE 30.- CHARACTERISTICS SUMMARY - MINIMUM DOC WITH 15¢ PER GALLON FUEL

	Pax 200 Range 1500	Pax 200 Range 3000	Pax 400 Range 3000
M_{CRUISE}	0.85	0.85	0.84
AR	7.1	8.2	6.8
t/c	13.0	11.7	13.3
TOGW	248 816	306 177	531 918
Wing Area	2145	2510	4255
W/S	116	122	125
T/W	0.32	0.282	0.27
Total Thrust	79 620	86 340	143 616
Wing Sweep	28°	28°	28°
Block Fuel	36 401	74 162	134 133
Payload (58% Pax)	23 200	23 200	46 400
OEW	159 060	178 512	293 482

TABLE 31.- CHARACTERISTICS SUMMARY - MINIMUM DOC WITH 30¢ PER GALLON FUEL

	Pax 200 Range 1500	Pax 200 Range 3000	Pax 400 Range 3000
M_{CRUISE}	0.82	0.82	0.81
AR	8.6	9.3	8.6
t/c	13.4	12.8	13.9
TOGW	246 850	303 251	524 993
Wing Area	2057	2527	4200
W/S	120	120	125
T/W	0.32	0.28	0.27
Total Thrust	78 988	84 908	141 748
Wing Sweep	26°	26°	25°
Block Fuel	33 562	70 601	122 065
Payload (58% Pax)	23 200	23 200	46 400
OEW	160 634	179 572	300 066

TABLE 32.- CHARACTERISTICS SUMMARY - MINIMUM DOC WITH 60¢ PER GALLON FUEL

	Pax 200 Range 1500	Pax 200 Range 3000	Pax 400 Range 3000
M_{CRUISE}	0.81	0.78	0.76
AR	9.9	11.8	10.8
t/c	13.4	14	15.1
TOGW	249 529	305 145	531 863
Wing Area	2079	2543	4255
W/S	120	120	125
T/W	0.32	0.28	0.27
Total Thrust	79 848	85 440	143 600
Wing Sweep	25°	25°	25°
Block Fuel	32 354	66 275	115 556
Payload (58% Pax)	23 200	23 200	46 400
OEW	164 847	186 291	314 308

TABLE 33.- CHARACTERISTICS SUMMARY - MINIMUM FUEL

	Pax 200 Range 1500	Pax 200 Range 3000	Pax 400 Range 3000
M_{CRUISE}	0.75	0.75	0.75
AR	14.0	13.4	12.7
t/c	15.0	14.0	15.5
TOGW	261 547	313 394	550 630
Wing Area	2144	2612	4477
W/S	122	120	123
T/W	0.325	0.28	0.27
Total Thrust	85 000	87 748	146 464
Wing Sweep	25°	25°	25°
Block Fuel	30 777	65 144	113 466
Payload (58% Pax)	23 200	23 200	46 400
OEW	178 943	195 652	335 129

TABLE 34.- CALCULATED FUEL CONSUMPTION - NEW NEAR-TERM 30¢ FUEL DESIGN 200 PAX/1500 N.MI. RANGE

Stage Length n.mi.	Fuel Consumption			
	lb	gal/n.mi.	seat-n.mi./gal	Btu/seat-n.mi.
100	3000	4.42	45.33	2790
200	5400	3.97	50.38	2511
400	9600	3.53	56.67	2232
600	13 800	3.38	59.13	2139
1000	21 700	3.19	62.67	2018
1500	31 400	3.08	64.97	1947
2000	41 700	3.07	65.23	1939
2449	51 134	3.07	65.14	1942
475	11 144	3.45	57.60	2190

TABLE 35.- CALCULATED TOTAL OPERATING COSTS - NEW NEAR-TERM 30¢ FUEL DESIGN 200 PAX/1500 N.MI. RANGE

Stage Length n.mi.	Block Speed kt	Total DOC*		Total IOC*	
		$/blk-hr	¢/seat-n.mi.	$/blk-hr	¢/seat-n.mi.
100	235	1326	2.85	3731	8.02
200	293	1190	2.02	2520	4.28
400	348	1106	1.59	1726	2.48
600	376	1070	1.43	1394	1.86
1000	410	1039	1.27	1106	1.35
1500	428	1028	1.20	940	1.10
2000	438	1011	1.16	849	0.97
2449	443	1010	1.14	840	0.95
475	360	1090	1.49	1570	2.15

*for 15¢/gal Fuel Cost

TABLE 36.- CALCULATED TOTAL OPERATING COSTS - NEW NEAR-TERM 30¢ FUEL DESIGN 200 PAX/1500 N.MI. RANGE

Stage Length n.mi.	Block Speed kt	Total DOC*		Total IOC*	
		$/blk-hr	¢/seat-n.mi.	$/blk-hr	¢/seat-n.mi.
100	235	1482	3.19	3739	8.04
200	293	1383	2.35	2440	4.15
400	348	1293	1.86	1736	2.50
600	376	1264	1.69	1404	1.87
1000	410	1239	1.51	1116	1.36
1500	428	1222	1.43	930	1.09
2000	438	1216	1.39	860	0.98
2449	443	1213	1.37	820	0.93
475	360	1285	1.76	1590	2.18

*for 30¢/gal Fuel Cost

TABLE 37.- CALCULATED TOTAL OPERATING COSTS - NEW NEAR-TERM 30¢ FUEL DESIGN 200 PAX/1500 N.MI. RANGE

Stage Length n.mi.	Block Speed kt	Total DOC*		Total IOC*	
		$/blk-hr	¢/seat-n.mi	$/blk-hr	¢/seat-n.mi.
100	235	1795	3.86	3756	8.08
200	293	1733	2.95	2460	4.18
400	348	1668	2.40	1756	2.52
600	376	1651	2.20	1424	1.90
1000	410	1638	2.00	1137	1.39
1500	428	1632	1.90	960	1.12
2000	438	1626	1.86	881	1.01
2449	443	1625	1.83	840	0.95
475	360	1660	2.27	1605	2.20

*for 60¢/gal Fuel Cost

6. RECOMMENDATIONS OF FUEL SAVING OPTIONS - TASK 6

The objective of this task was the selection of the airplanes to be employed in the air transportation system analysis studies by United Technologies Research Center (UTRC). These airplanes were to include the current aircraft representative of the United States domestic fleet and airplanes selected by the airframe manufacturers from the foregoing tasks of the study. The latter includes selections from current aircraft operating with procedure changes, modifications to and derivatives of current aircraft and all new aircraft designs (Tasks 2 through 5).

Because one of the main results of the selection process was to arrive at a fleet mix of aircraft for the UTRC study that was representative of the average domestic fleet, United Airlines also submitted fuel and cost data for their fleet. In this way, current airplanes not included in the airframe manufacturers Task 1 studies were made available.

It became obvious at this stage of the study that, for a set of data to be representative of the average domestic fleet, it would necessarily have to include data from both the airframe and airline contractors. This in turn meant that performance data based on different sources would need to be made consistent. The airframe manufacturers used handbook (ideal) performance levels and generated their data using the agreed to flight profiles while the United Airlines data was representative of their fleet experience in day to day operation. Coordination among the contractors and NASA led to the recommendation that the United Airlines service data be used for the current aircraft task and that the manufacturers data be used in all of the other tasks with appropriate factors applied to result in estimated airline service data for all tasks. This method insured that the UTRC objective of estimating future fleet fuel usage as realistically as possible was met.

The factors applied to the airframe manufacturers handbook data (airline factors) account for air traffic control delays and routing, weather, performance deterioration, and the other items which make up the difference between ideal and in-service performance. These were developed by comparing block time and block fuel data for aircraft common to both the United and Douglas data base, the DC-10-10 and the DC-8-50. These comparisons, reproduced here as Figures 19 and 20, show that in terms of block time, the differences between handbook and in-service were in close agreement for both aircraft. A shift was noted in the block fuel comparisons, and it was assumed to be caused by the difference in service life of the DC-10-10 and the DC-8-50. The DC-10 aircraft in the United fleet showed closer correlation with the handbook calculated block fuel data than the DC-8-50 aircraft which are considerably older, and presumably, experiencing more performance deterioration. It was therefore decided to use an average factor based on these data as indicated by the fairing shown in Figure 20 to arrive at a mid-service life fleet of aircraft.

The airline factors plus the aircraft options to be considered in the UTRC fleet system studies were developed at a coordination meeting held on August 11 and 12, 1975, between the contractors and the NASA technical monitor. As discussed above, the factors are those shown in Figures 19 and 20. The

aircraft options to be considered in three of the five classifications in the UTRC study, the source of these data and the usage of the airline factor were also determined at the coordination meeting. For completeness, these data as originally released by NASA are reproduced here as Tables 38, 39, and 40. In Table 38, Current Aircraft, note that an airline fuel factor was also applied at a constant percentage to the existing wide bodied aircraft. This was done to adjust the United Airline's data on these aircraft to mid-service life. Also note that in Tables 39 and 40, Modified and Derivative Aircraft, respectively, although usage of the airline factor is not specified, both the block time and block fuel factors were to be applied to these data as supplied by the airframe manufacturers. These airline adjustments are discussed in Reference 3.

Agreements on the remaining two tasks, Task 2, Operational Procedure Changes, and Task 5, New Near-Term Aircraft, were also concluded at the August 11-12, 1975 coordination meeting.

Lockheed and Douglas agreed on further coordination to (1) develop a list of fuel saving operational procedures which could be applied by UTRC on a basis consistent with their adopted baseline aircraft data, and (2) determine if common Lockheed/Douglas new near-term aircraft performance data could be derived. A list of percentage fuel savings for each aircraft in the UTRC base was developed for both the current air traffic control system and an advanced air traffic control system. These data are reproduced here as Table 41. An important point here is that it was not the intent of this study to identify the costs involved with an improved ATC System; rather the fuel savings which would be possible if such a system existed were to be identified. In this way, any large cumulative fuel savings resulting from the UTRC study could serve as an incentive for further study in this area.

In the new near-term aircraft of Task 5, it was determined that a common set of performance data could be generated from that developed by each airframe manufacturer. The derived airplane geometries in each of the payload/range classes were in close agreement so that average values of block fuel, block time and operating costs were reasonable to assume. The minimum fuel designs differed in the wing sweep parameter. The Douglas designs incorporated a straight wing while the Lockheed designs used a quarter chord sweep angle of 25 degrees. It was determined that the Douglas minimum fuel designs could possibly be oversized for present airports due to their large wing spans and in addition their low cruise Mach numbers might be incompatible with current airline fleets. On this basis, the Lockheed swept wing designs were used with the fuel and cost data modified to retain consistency with the averaged minimum cost design airplanes.

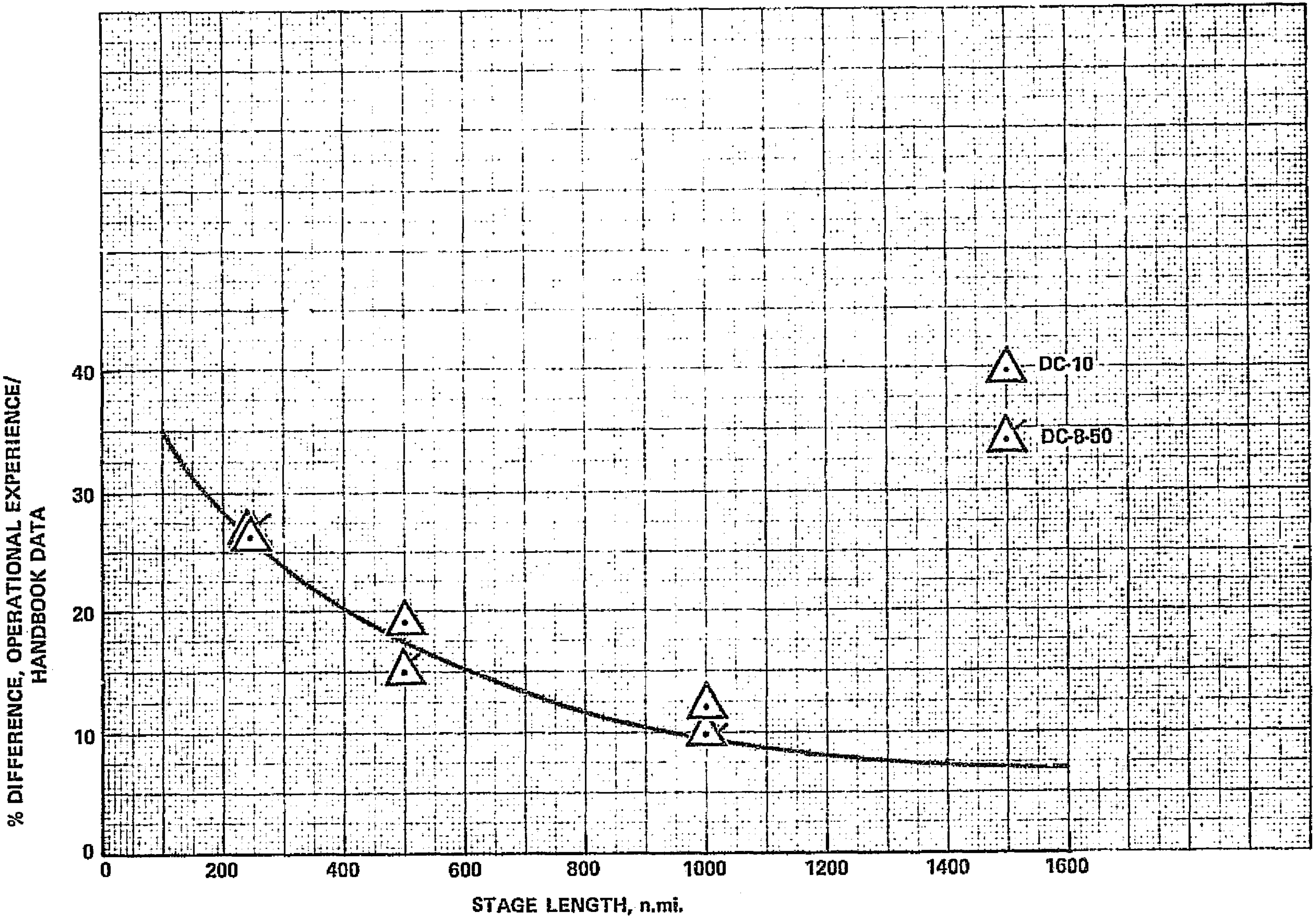


Figure 19.—Airline factor - block time

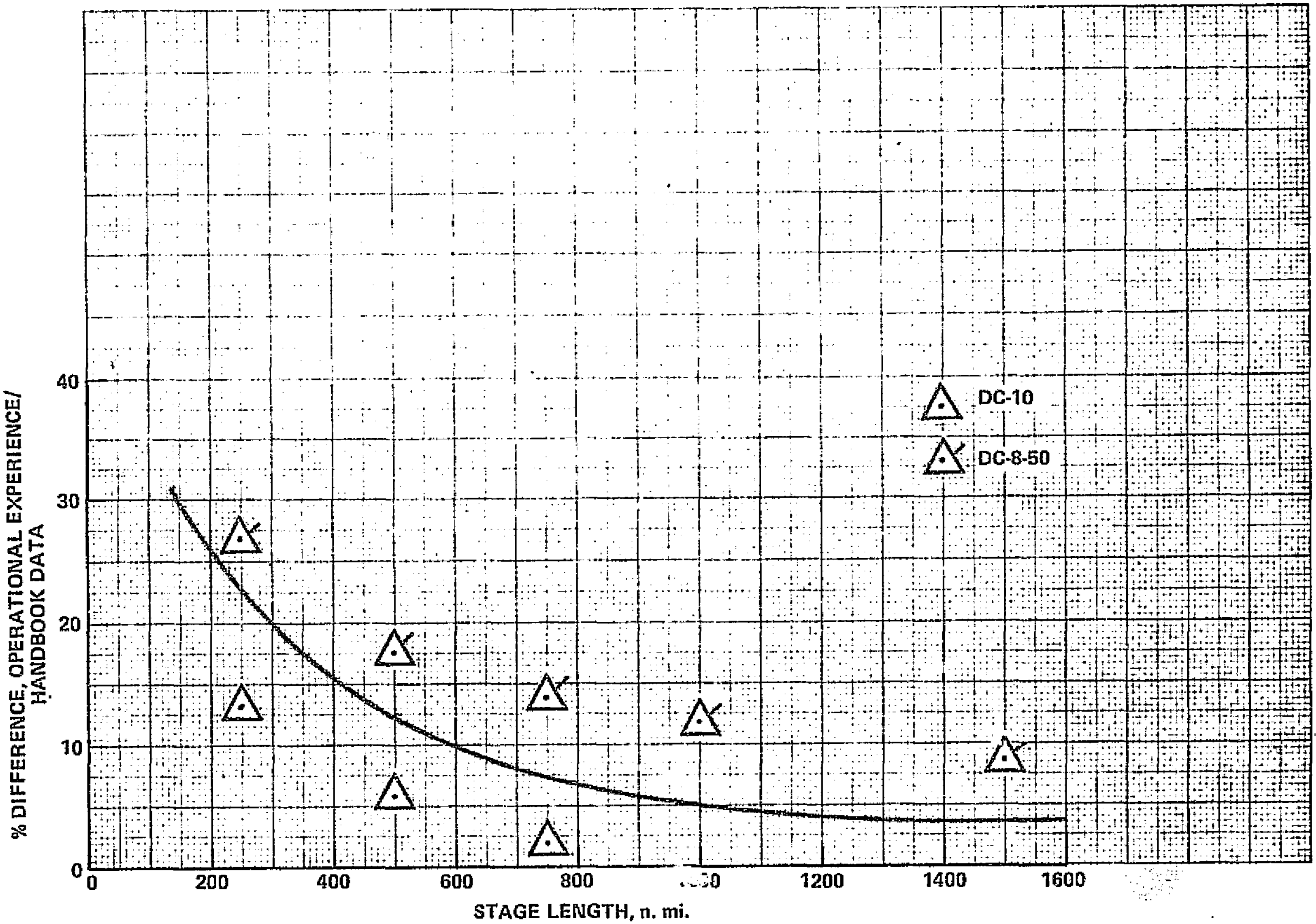


Figure 20.—Airline factor - block fuel

TABLE 38.- CURRENT AIRCRAFT-UTRC STUDY

Aircraft	Data Source	Airline Factor? Time	Airline Factor? Fuel
Existing:			
DC-9-10	DAC	Yes	Yes
727-100	UAL	No	No
DC-8-50 (707-120B, 720B)	UAL	No	No
DC-8-62 (707-320B)	UAL	No	No
DC-8-61	UAL	No	No
DC-8-20 (880, 720)	UAL	No	No
747-100	UAL	No	Yes(3-1/2%)
Existing & Eligible for New Buys:			
DC-9-30	DAC	Yes	Yes
737-200	UAL	No	No
727-200	UAL	No	No
DC-10-10 (L-1011-1)	UAL	No	Yes(4-1/2%)
747-200	UAL	No	Yes(3-1/2%)

TABLE 39.- MODIFICATIONS - UTRC STUDY

RETROFIT MODIFICATIONS
AERODYNAMIC ONLY

Aircraft	Modification	Average Fuel Saving
L-1011	Wingtip extensions (2-1/2%) and engine afterbody (3-1/2%)	7-1/2%
DC-10	Winglets (4%), wing root fairings and drag cleanup (5%)	
747		
DC-8-20, 50, 61 (707-120B, 720B)	Winglets (2%) and drag cleanup (3%)	5%
DC-8-62 (707-320B)	Winglets (2%)	2%
DC-9-10, 30 727-100, 200 737-200	Winglets (1-1/2%) and drag cleanup (2-1/2%)	4%

RETROFIT MODIFICATIONS
AERO AND ENGINE

(Includes all modifications in previous "Aerodynamic Only Retrofit Case" with the following additions:)

Aircraft	Modification	Average Fuel Saving
DC-8-20	Winglets, drag cleanup and JT8D Refan	35%
DC8-50, 61 (707-120B, 720B)	Winglets, drag cleanup and JT8D Refan	15%
DC8-62 (707-320B)	Winglets and JT8D Refan	12%

TABLE 40.- DERIVATIVES - UTRC STUDY

Aircraft	Passenger Payload	Range (n.mi.) @ 100% Passenger Payload
DC9-50 with winglets	117	2000
DC10-10 D1	200	2640
L-1011 Short Body	200	1920
DC10-40 D1 (DC10-30 + 30 ft stretch, 10 ft wingspan extension and winglets)	327	3500+
L-1011 Long Body	400	2160
727-300	157	1970

TABLE 41.- OPERATIONAL PROCEDURES CHANGES - UTRC STUDY

Aircraft Model	Designation UTRC Study	Baseline Mach	CAB Av. Block Distance (n.mi.)	Percentage Reduction in Block Fuel								
				With Current ATC						With Improved ATC		
				Reduce Speed to LRC	2000 Foot Step Climb	Load to Aft c.g.	A/P Cleanup	Reduce OEW 1%	Improved Engine Standard	Climbing Cruise	Reduced Delays: Holding	Reduced Delays: Terminal
In Production												
DC-9-30	C2ELBD	0.73	290	0*	0*	0.2	0.4	0.3	0.5	0*	1.6	2.5
B737-200	C2ELBB	0.73	266	0*	0*	0.2	0.4	0.3	0.5	0*	1.7	2.7
B727-200	C3ELB	0.80	421	0.2	0.1	0.2	0.5	0.5	0.5	0.1	1.1	1.7
DC-10-10 L-1011-1	C3EHB	0.83	870	1.0	0.3	0.2	0.5	0.4	1.0	0.4	0.7	1.0
B747-200	C4EHB	0.84	1616	1.2	0.5	0.2	0.5	0.5	1.0	0.5	0.4	0.5
Out of Production												
DC-9-10	Same	0.73	300	0.4	0*	0.2	0.4	0.2	0.5	0*	1.5	2.6
B727-100	Same	0.80	477	0.2	0.1	0.2	0.5	0.4	0.5	0.1	1.0	1.7
DC-8-20 (CV880, B720)	Same	0.80	862	1.0	0.3	0.2	0.5	0.4	0.3	0.4	0.8	1.9
DC-8-50 (B120B, 720B)	Same	0.80	731	1.0	0.3	0.2	0.5	0.4	0.3	0.4	0.8	1.9
DC-8-62 (B707-320B)	Same	0.80	1243	1.0	0.3	0.2	0.5	0.4	0.3	0.4	0.8	1.9
DC-8-61	Same	0.80	800	1.0	0.3	0.2	0.5	0.4	0.3	0.4	0.8	1.9

*No cruise, step cruise or cruise climb at 1973 CAB average block distance.

7. CONTRACT FOLLOW-ON 1985 TURBOPROP/TURBOFAN AIRCRAFT STUDY - TASK 7

The fuel saving advantages of the turboprop propulsion system, identified in Task 5, led to a modification to the contract encompassing additional follow-on studies of this propulsion system. The turboprop airplanes studied in Task 5 were limited to cruise speeds in the Mach 0.6 to 0.7 range by the conventional propeller designs employed. Utilization of these state-of-the-art propellers was dictated by the 1980 service introduction date specified in Task 5. Because operation at Mach 0.6 to 0.7 is not practical in the current air traffic control environment and since the longer block times adversely affect direct operating costs by increasing crew costs and decreasing utilization, the follow-on study envisioned turboprop operation at a more compatible cruise speed of Mach 0.80.

Conventional propellers exhibit a sharp falloff in efficiency beyond approximately Mach 0.65 as the compressibility effects on the blading become significant. A new design high speed propeller which delays these compressibility effects to higher Mach numbers has been identified by the Hamilton Standard Division of United Technologies Corporation (Refs. 6 and 7). This concept, designated the Prop-Fan, is a multibladed, highly loaded and variable pitch propeller that is envisioned to be used with an advanced turboshaft engine. The blades are thin, incorporate tip sweep, use supercritical airfoils, and are integrated with a spinner/nacelle shape designed to reduce the speed of the axial flow through the blades. The Prop-Fan will be able to operate at Mach numbers competitive with the turbofan. Figure 21, showing an advanced turboprop aircraft model developed under Lockheed independant development funds, typifies the Prop-Fan installation concept.

The objective of the follow-on effort, identified as Task 7 was to examine the potential of this new propulsion system when installed in an advanced technology airframe. Comparison of a propfan/turboprop airplane with an equal technology airplane equipped with turbofan engines was the method used to assess the potential. The desired result of this comparison was the definition of the research and technology required to ultimately implement the propfan/turboprop concept assuming that adequate benefits were shown.

In order to ensure that realistic propulsion data were utilized in the comparisons, an engine manufacturer and a propeller manufacturer were employed as subcontractors for this task. Both the Pratt and Whitney and the Hamilton Standard Divisions of United Technologies Corporation were included, and in addition, Eastern Air Lines was employed as consultant. Pratt and Whitney's responsibility included the supply of engine data for both the JT10D turbofan and a rematched version of the STS476 turboshaft engine. The JT10D is a ten tonne engine of high-bypass ratio which exhibits specific fuel consumption levels comparable to current high-bypass engines such as the RB.211, JT9D, and CF-6. The STS476 is a Pratt and Whitney study turboshaft engine with component technologies comparable to the JT10D. Hamilton Standard had responsibility for performance data on the Prop-Fan including assistance in the selection of the specific configuration (disc loading, blade number, and diameter) to be employed

in this study. Eastern Air Line's role as consultant included overall study assessment from an airline operators standpoint. As the largest current operator of the Electra turboprop aircraft, their experience was sought in the area of passenger acceptance, maintenance and costs.

Ground rules established for the comparison study are listed below.

- Configuration
  - 200 Passenger
  - Wide Body Fuselage
  - 4 Engines

- Mission
  - M 0.80 Cruise, 1500 n.mi.
  - Initial Cruise Altitude $\geq$ 30 000 Feet
  - Field Length $\leq$ 7000 Feet
  - Approach Speed = 135 Knots

A prime consideration in establishing these ground rules was to maintain compatibility with the new near-term design airplanes of Task 5. In this way advantage was taken of the extensive parametric design study performed in that task. The airplane designed for minimum direct operating cost with 60 cents per gallon fuel was selected from Task 5 with concurrence of NASA as the baseline design for both the turboprop and turbofan aircraft of this study.

A reoptimization of these baseline designs was then employed to further refine the aircraft and to include technologies commensurate with the 1985 initial service date. Advanced composite materials and active flight controls were incorporated in both designs; these technologies allow the use of a smaller, lighter airframe to accomplish the design mission. Only cost-effective secondary structure was considered for composites application and this usage resulted in an empty weight reduction of 3.3 percent before the effects of resizing were considered. In the study airplanes, secondary structure employing composite materials includes the wing fixed leading edge, fuel tank baffles, floor supports, interior doors, and dividers. Active ailerons which provide maneuver and gust load alleviation through an inboard transfer of spanwise wing loads give a three percent reduction in wing weight. Relaxation of the static stability margins through the use of an active horizontal tail, results in a reduction in tail size and a corresponding reduction of 30 percent in tail weight. The total empty weight reduction due to the inclusion of active controls in the study airplane designs was 1.2 percent.

Incorporation of advanced composites and active controls commensurate with the 1985 study airplane time period resulted in a total empty weight reduction exclusive of resizing effects of 4.5 percent. To account for these weight benefits and also for the incorporation of the specific engines selected for both the turbofan and the turboprop design, further parametric studies were performed. For both airplanes, variations in wing and power loadings combined with the mission constraints were used to define the point design airplanes. In each case minimum direct operating cost was used as the selection criterion.

The final turbofan design, including detailed performance characteristics, was determined at this stage of the study and the remainder of the effort was devoted to the detailed design and performance computations for the turboprop airplane. The general thrust requirements of the turboprop airplane were defined from the reoptimization study and further parametrics were used to define the sensitivities of airplane sizing to propeller diameter/disc loading. Using these data, the subcontractors, Pratt and Whitney and Hamilton Standard rematched the engine and Prop-Fan system to meet the airplane requirements. The final aircraft assessments, the comparisons and the determination of sensitivity to changes in the basic parameters were the concluding work performed.

7.1 Turbofan Concept

The point-design turbofan airplane concept is shown in the general arrangement drawing of Figure 22. The aspect ratio 10 and sweep of 25 degrees for the supercritical wing are, as discussed previously, the results of the minimum operating cost/high fuel cost environment design philosophy. The very small horizontal tail surfaces are the result of the incorporation of active flight controls to allow relaxed static stability. As shown in Figure 22, the other aspects of the design are conventional. The four engines are mounted under the wing on pylons; this arrangement having been proven to offer the lowest drag and interference penalties while offering superior maintenance accessibility. In the CL 1320-11 (Figure 22) design, engine ingestion of runway debris is not a concern; the clearance between the ground and the lower inlet lip is 76 inches. Part of this clearance is the result of the landing gear length being designed to maintain adequate tail clearance on aircraft rotation, but it is also partly the result of the relatively small engines required. As previously noted, the Pratt and Whitney JT10D-2 engine was scaled for this application; the resulting sea level static thrust rating is 14 672 pounds per engine.

7.2 Turboprop Concept

While the turboprop aircraft can, in general, retain the geometry of the turbofan design, several turboprop - unique considerations must be taken into account. These considerations involve the installation design of the propulsion system and the calculation of the turboprop aircraft performance. The Prop-Fan concepts being studied by Hamilton Standard include various propeller configurations in terms of blade number and tip speed. At the initiation of this study, their efforts indicated that an eight-bladed Prop-Fan operating at a tip speed of 800 feet per second was near optimum. Blade number and tip speed were therefore held constant. Installation guidelines also developed by Hamilton Standard were applied where appropriate.

The primary considerations in the installation of the turboprop propulsion system are the selection of the propeller disc loading, the nacelle configuration and the spanwise location of the propulsion units on the wing. Selection of the propeller disc loading and diameter is dependent upon the tradeoff between propeller efficiency and installation weights and the impact on aircraft performance. These effects were examined through propeller sensitivity studies involving the parametric design of a large number of additional aircraft. Again

using minimum direct operating cost as the criterion, an envelope of aircraft meeting the design constaints but employing different propeller diameters resulted. The performance variation was found to be quite insensitive to propeller diameter, but the smallest diameter gave the lowest operating cost. The propeller weight penalty paid for the improved efficiency of larger diameter is the major factor in driving the selection to the smaller diameter. This penalty is magnified by the additional weight penalties which accrue when the larger diameter propeller is installed on the airplane. Additional structure is necessary in elements such as the gearboxes, nacelles, and wing. All of these weight effects are cummulative and other aircraft structures are impacted as resizing is required to maintain the design mission range.

Several nacelle configurations were considered in the design of the turboprop aircraft. The final selected design is an underwing design employing an offset gearbox and a scoop inlet. The aerodynamic shape of the nacelle is determined by the desired flow velocity through the root sections of the propeller and it is expected that this aerodynamic shape will dictate the overall nacelle size rather than any limitations imposed by the housing of the necessary internal components. Guidelines established by Hamilton Standard were used in this determination as well as in the spanwise location of the propellers. In the latter case, these guidelines resulted in widely spaced propellers located considerably further away from the fuselage side than has been the case on past turboprop aircraft.

The basic characteristics of the turboprop installation introduce differences that require careful performance accountability when compared to the turbofan aircraft. The most obvious of these is the drag treatment to allow for propeller slipstream effects. Also to be considered are the nacelle/wing interference drag and the acoustic environment at the external fuselage wall produced by the propfan operating at supersonic tip speeds during cruise. Each of these items were examined and the assessment and results are discussed in detail in the companion final report, Reference 4.

The general arrangement of the resulting turboprop aircraft, Figure 23, is not dramatically different from the turbofan aircraft. Overall dimensions of length and span are nearly identical. A rematch version of the Pratt and Whitney STS476 study turboshaft engine is used with the 12.6 foot diameter eight-bladed propfan which resulted from the final aircraft synthesis.

Table 42 compares the general characteristics of the two airplane point designs and Table 43 presents descriptive features of the respective propulsion systems. As noted in Table 42, the takeoff weights required to perform the design mission are nearly identical; the largest weight difference is seen to be in the operational empty weight comparison. The propfan/turboprop engine features noted in Table 43 represent the engine as rematched by Pratt and Whitney for the study aircraft requirements and includes a completely new compressor and low pressure turbine. As shown, the sea level static thrust ratings of the two installations are nearly equal. Note, however, that the maximum rating for the turboshaft engine occurs at the beginning of climb; this accounts for the two shaft horsepower ratings shown. While the combustor exit

temperatures are equal, the overall pressure ratio of the STS476 engine is lower as the result of the loss of fan supercharging. While methods of regaining the supercharging at the cost of additional complexity are available with an attendant gain in SFC up to approximately three percent, Pratt and Whitney did not make this change for this study. The final technical memorandum received from Pratt and Whitney discusses the turboshaft engine in more detail and the reader is referred to Appendix A of the final technical report, Reference 4.

7.3 Performance, Economic and Characteristics Comparisons

At this stage of the study, the turbofan and turboprop powered airplanes had both been developed using 1985 levels of technology. Both had been designed to the same payload-range requirements and to the same mission constraints. The airplanes are competitive in terms of cruise speed, cruise altitude, and block time, and both offer equal passenger comfort.

Significant differences appear when the fuel and cost to operate these aircraft are compared. At the full design passenger payload and at the design range of 1500 nautical miles, the turboprop airplane consumes 17.8 percent less fuel with a 5.3 to 8.2 percent lower direct operating cost, as shown in Figure 24. The direct operating cost comparisons are made for fuel at the design cost of 60 cents per gallon, and also at a fuel cost of 30 cents per gallon. If the comparison is made at a typical in-service stage length of 475 nautical miles with the study load factor of 58 percent, Figure 25 shows that the turboprop airplane uses 20.4 percent less fuel while offering operating cost advantages of 8.5 and 5.9 percent for the two fuel costs.

These differences in fuel and operating costs are caused by differences in engine specifics, and airplane weight and drag. The most pronounced difference is in the propulsion systems. At maximum cruise power the STS476 turboprop engine has better than a 19 percent lower specific fuel consumption while at the maximum climb power setting the difference exceeds 26 percent on the average and exceeds 30 percent at the lower altitudes, as noted in Figure 26. Since climb represents a much larger percentage of total mission time on the shorter 475 nautical mile mission (nearly 32 percent) compared to the 1500 nautical mile design mission (12 percent), greater fuel savings for the turboprop relative to the turbofan occur as range is decreased.

Table 44 shows that the turboprop aircraft empty weight exceeds that of the turbofan airplane by 6.4 percent. The major difference in the component weights which cause this overall weight disparity are indicated in the table. The additional torsional loads introduced by the propeller account for two percent of the wing weight increase; further weight increases are caused by the multiplying factor of airplane resizing to perform the mission. Propeller loads are also the cause of the additional nacelle weight of the turboprop airplane. The total uninstalled propulsion system weight of the turboprop (including propeller and gearbox) is the major factor in the large installed weight penalty. Lower weights of some of the components needed to install the system partially compensate for the penalty. The most significant item is in the provisions required to provide thrust reversal. The variable pitch feature of the propeller offers a means of providing reverse thrust without the cascade and

blocker door or spoiler system required by the fixed pitch fan of the turbofan installation. Note that fan reverse only is used in the study turbofan concept; no provisions were made for reversing the flow of the primary jet exhaust. The largest weight increment shown in Table 44 is for the acoustic treatment in the turboprop airplane. This item is shown in the furnishings since the treatment area is the fuselage sidewall.

Differences in the drag of the two airplanes can be seen by examining the breakdown of Table 45. As in the previous table a comments column is used here to designate the major differences. The wing component drag on the turboprop airplane is slightly smaller by virtue of less wetted area and slipstream effects. The wing wetted area is reduced because of the larger nacelle/wing interface of the turboprop where no pylon is used. Some of this drag benefit is offset by the larger turboprop nacelle. However, the main difference between the nacelle drag components is caused by the higher wing/nacelle interference assessed for the turboprop installation. A compensating factor is the addition of the drag of the turbofan pylons. Table 45 shows that, when all of the drag components are summed, the total airplane drags are nearly identical.

A breakdown of the direct operating cost comparison is shown in Figure 27. The lower block fuel of the turboprop airplane accounts for the improvement in operating cost. These data were calculated for a fuel price of 60 cents per gallon.

A table summarizing these performance and economic comparisons is presented as Table 46. Here the basic comparison is made at the 1500 nautical mile design range with full passenger payload while the percentage change in fuel and operating cost at the typical in-service stage length is also indicated.

The potential improvements that may be available by using more advanced technologies in the propulsion system were also assessed. Use of a dual-rotation propfan offers improvements in efficiency of approximately five percent due to swirl recovery. A parametric study using this concept with advanced technology propulsion system weights and costs was performed using inputs from the propulsion equipment subcontractors (Appendices A and B of Reference 4). Figure 28 presents the results of this study. The baseline comparisons at the 1500 mile design range from Figure 24 are repeated here for both the fuel and cost data with the bars on the left for the turboprop airplane and the bars on the right for the turbofan airplane. The center bar shows that a four percent additional improvement in block fuel is obtained using the dual-rotation propfan and that the direct operating cost is improved by an additional 1.5 percent. The higher cost of this system, both acquisition and maintenance, is compensated for in the direct operating cost by the lower fuel usage and by the comensurate resizing of the airplane. This can be seen by noting the significant reduction in takeoff weight required to perform the design mission. While the dual-rotation propfan concept introduces additional complexity, the fuel saved and subsequent smaller airplane may compensate.

7.4 Sensitivities

Since little experimental work has been done in recent years on advanced technology propellers, theoretical performance predictions were used quite extensively in this study task. Of the many variables that can affect the study results, propeller efficiency, engine SFC, nacelle-wing interference, engine

weight, acoustic treatment, and maintenance cost are the most important. Variations in each of these parameters were studied separately and the effect on the block fuel and operating cost data expressed relative to the turbofan baseline is shown in Figures 29 through 34. The basic comparison at the 1500 nautical mile design point is shown at the circled point and the shaded band is shown to indicate reasonable ranges of variation. Each of the sensitivity trend curves reflect aircraft resizing to maintain study ground rule compliance. All of the operating costs shown in Figures 29 through 34 reflect a fuel cost of 60 cents per gallon.

Figures 29 and 30 show that even with a five percent degradation in propeller efficiency or engine SFC the propfan/turboprop concept would realize a fuel savings of 13 percent over the turbofan airplane. The corresponding direct operating cost savings are smaller but still significant. The fuel and cost savings are less sensitive to nacelle/wing interference and propulsion system weight, Figures 31 and 32 respectively. If the turboprop engine could be installed at the drag levels of a typical turbofan engine, a one percent improvement in the fuel and cost advantage result. Likewise, a one percent improvement in fuel and cost are obtained with further technology advances incorporated to save weight in the propulsion system. These fuel and cost savings, Figure 32, are obtained at the expense of slightly higher aircraft acquisition costs.

The sensitivity of turboprop fuel and cost characteristics to acoustic treatment weight is shown in Figure 33. If exterior sound levels at the fuselage sidewall should prove to be 10 dB higher than currently predicted, the acoustic treatment weight penalty more than doubles to over 7000 pounds and the fuel advantage is degraded to approximately 15 percent. If research and testing indicates that the fuselage fore and aft area requiring noise treatment for shock impingement can be reduced 50 percent, and/or lighter methods of treatment can be found, the fuel and cost advantages could improve by approximately one percent.

Figure 34 shows that a ten fold increase in the maintenance costs does not eliminate the direct operating cost advantage of the propfan/turboprop aircraft. Even at these elevated levels, the propfan/turboprop has a five percent direct operating cost advantage for fuel at 60 cents per gallon, as well as the 18 percent block fuel advantage.

Maintenance hours and cost will be of major concern to those who consider operation of future turboprop powered airplanes. Loss of the improvements made in this area when the airlines transitioned from reciprocating engined/propeller driven aircraft to turbojet powered aircraft is certainly not desired. The turboprop concept studied here, however, is not a design that can be compared to these previous propeller driven aircraft that were based on 1950 levels of technology. Advances that have been made in modular design of the current turbofan engines would be applied to the propeller (propfan) and gearbox as well as to the engine in the propfan/turboprop concept. Two decades of gearbox technology advances reflecting helicopter transmission development are available. The elimination of high maintenance cost items such as fan thrust reversers and the alleviation of wheel and brake maintenance also work to the propfan/turboprop airplane's advantage. All of these items are significant in producing the projected reduced maintenance cost levels shown in Figure 34.

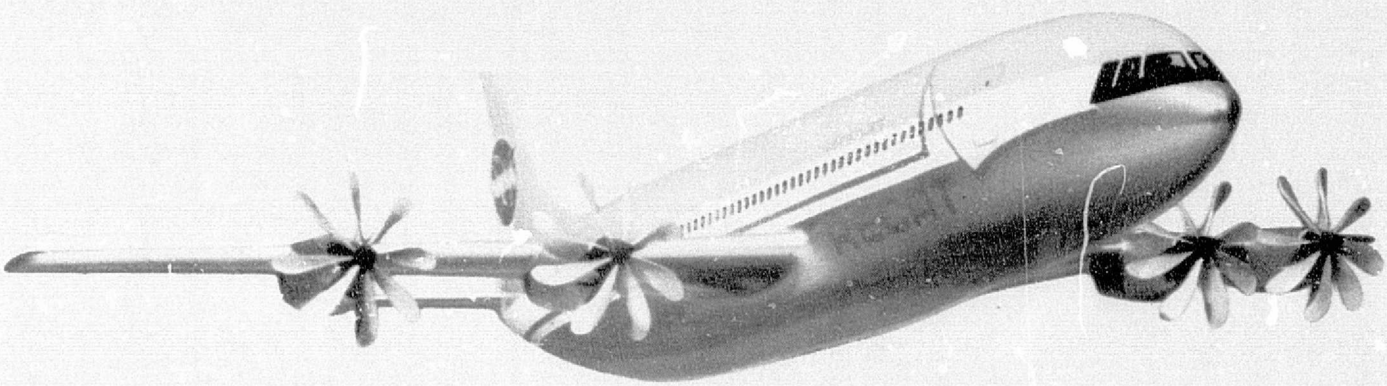
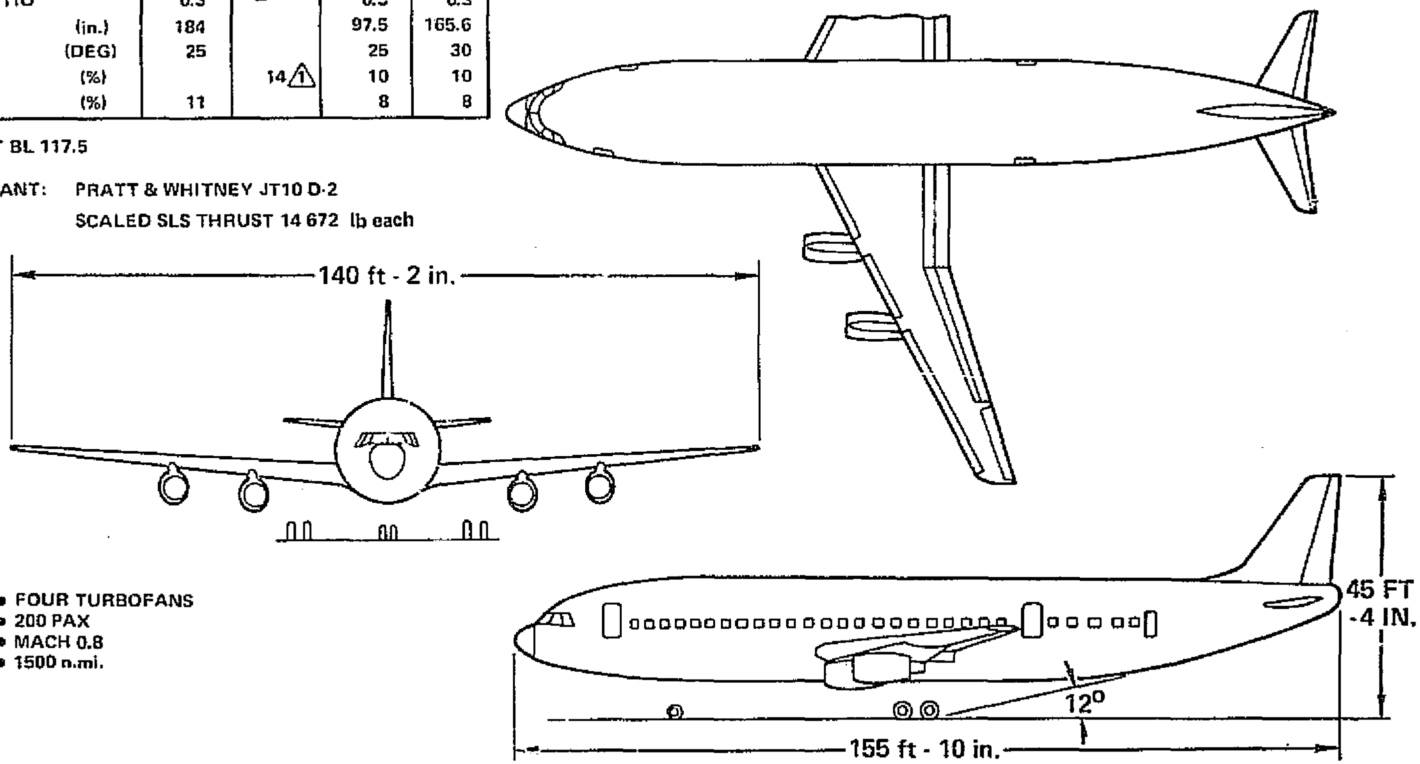


Figure 21.—Advanced turboprop airplane concept

CHARACTERISTICS		WING BASIC	WING TOTAL	HORIZ	VERT
AREA	(ft^2)	1955	2209	275	253
ASPECT RATIO		10	–	5	1.6
SPAN	(ft)	139.8		37	20.1
ROOT CHORD	(in.)	258	303 ⚠1	137	232
TIP CHORD	(in.)	77		41	70
TAPER RATIO		0.3	–	0.3	0.3
MAC	(in.)	184		97.5	165.6
SWEEP	(DEG)	25		25	30
T/C ROOT	(%)		14 ⚠1	10	10
T/C TIP	(%)	11		8	8

⚠1 AT BL 117.5

POWER PLANT: PRATT & WHITNEY JT10 D-2
SCALED SLS THRUST 14 672 lb each



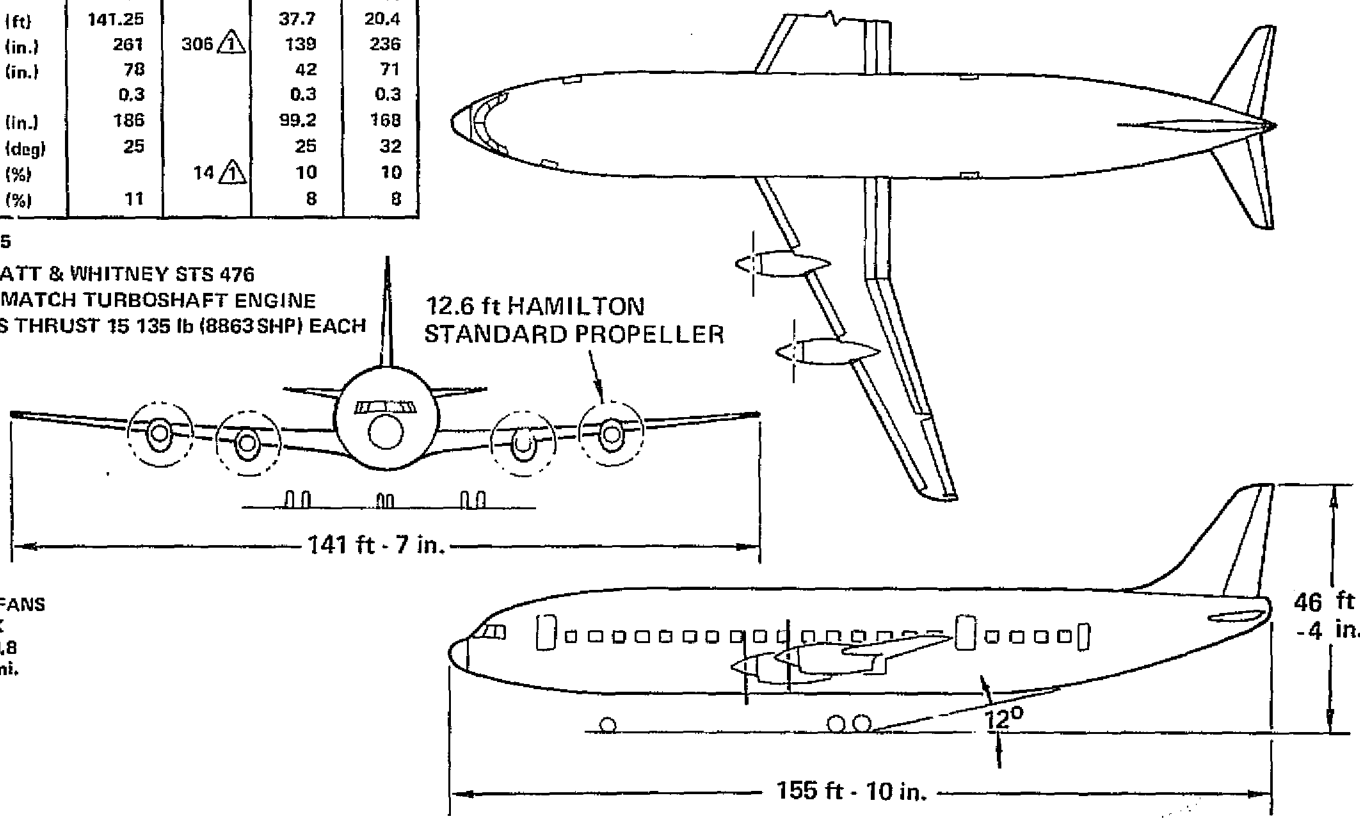
- FOUR TURBOFANS
- 200 PAX
- MACH 0.8
- 1500 n.mi.

Figure 22.—General arrangement - turbofan aircraft

CHARACTERISTICS		WING BASIC	WING TOTAL	HORIZ	VERT
AREA	(ft^2)	1995	2250	284	261
ASPECT RATIO		10	—	5	1.6
SPAN	(ft)	141.25		37.7	20.4
ROOT CHORD	(in.)	261	306 ⚠1	139	236
TIP CHORD	(in.)	78		42	71
TAPER RATIO		0.3		0.3	0.3
MAC	(in.)	186		99.2	168
SWEEP	(deg)	25		25	32
T/C ROOT	(%)		14 ⚠1	10	10
T/C TIP	(%)	11		8	8

⚠1 AT BL 117.5

POWER PLANT: PRATT & WHITNEY STS 476
REMATCH TURBOSHAFT ENGINE
SLS THRUST 15 135 lb (8863 SHP) EACH



- 4 PROPFANS
- 200 PAX
- MACH 0.8
- 1500 n.mi.

Figure 23.—General arrangement - propfan aircraft

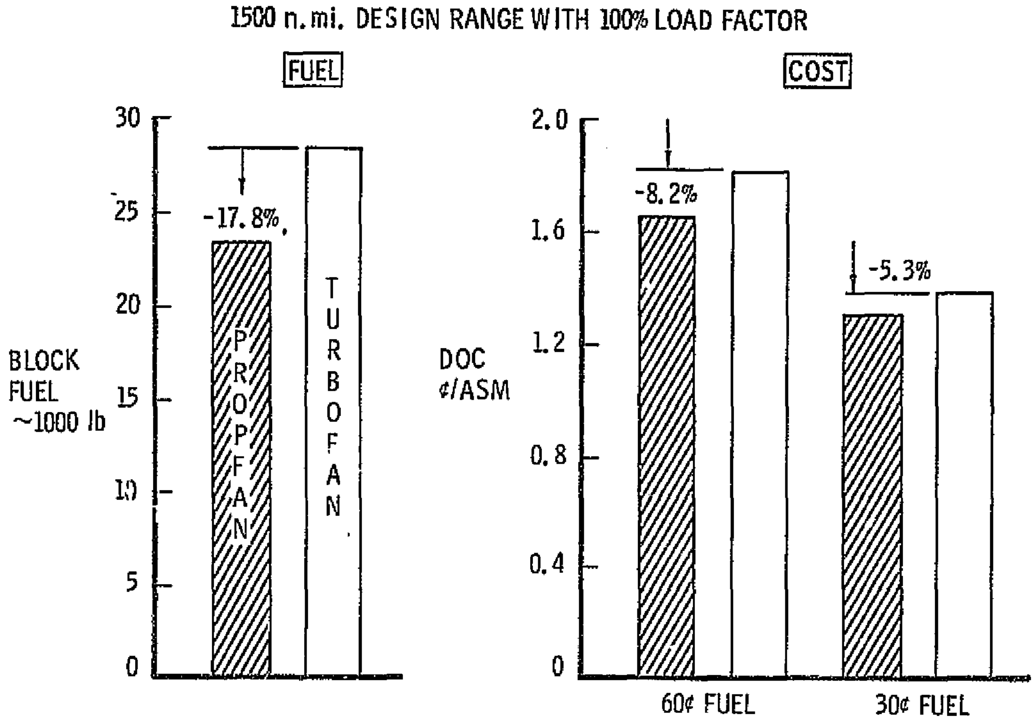


Figure 24.-Aircraft comparisons - 1500 n.mi. design range

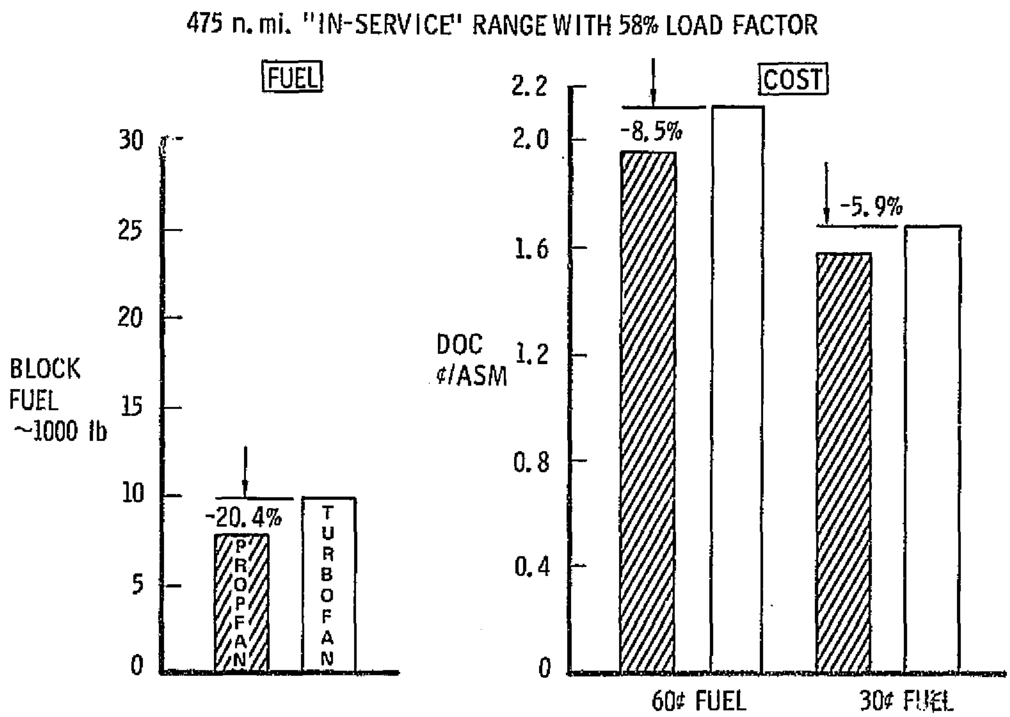


Figure 25.-Aircraft comparisons - 475 n.mi. in-service range

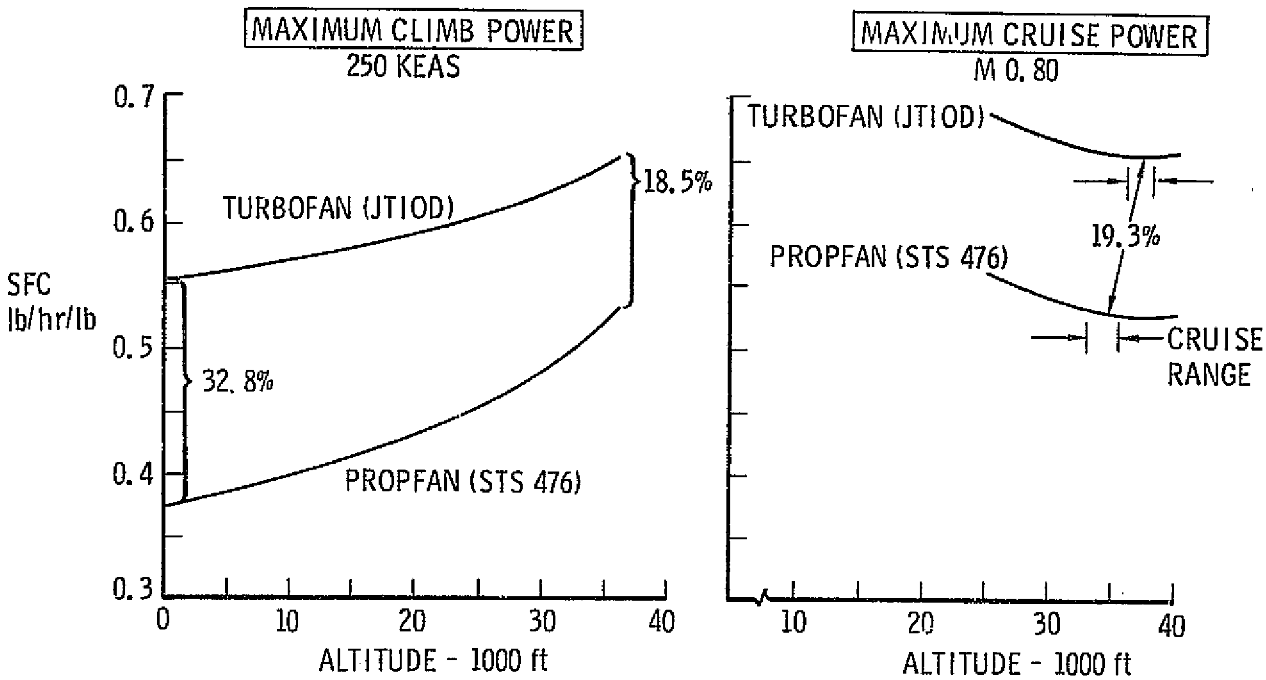


Figure 26.—Comparison of installed specific fuel consumption

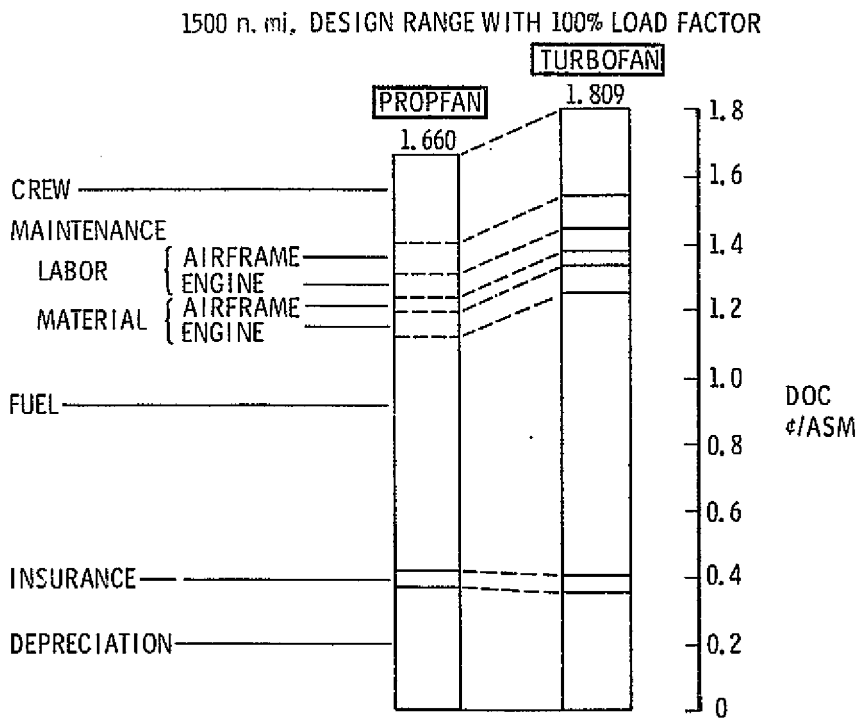
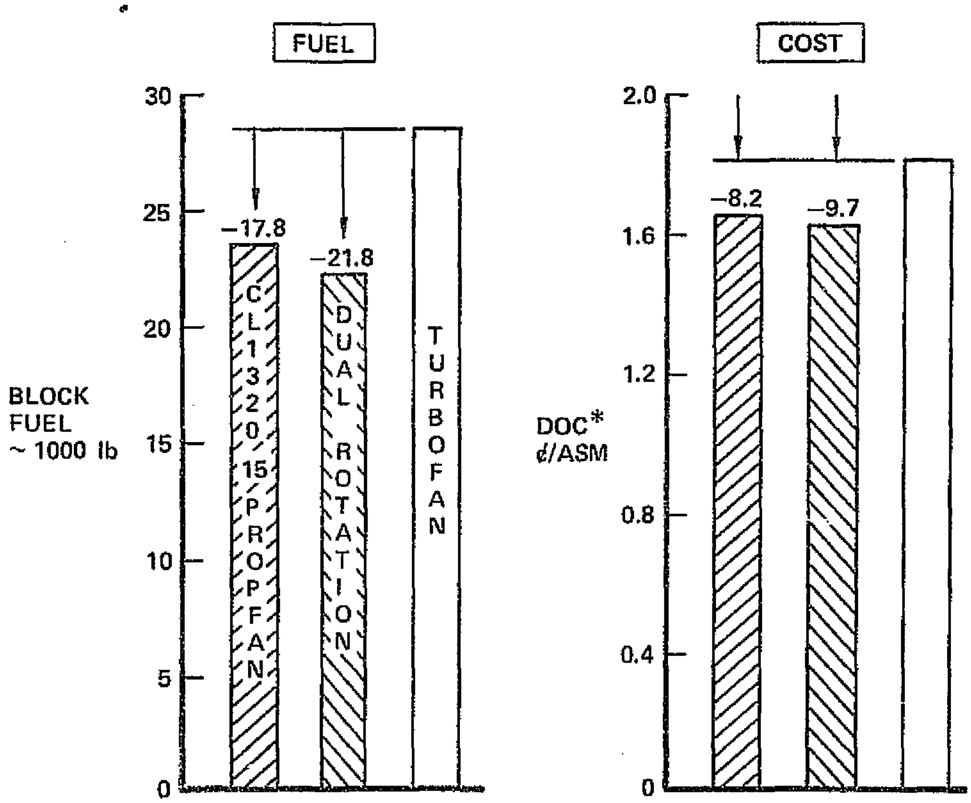


Figure 27.—Direct operating cost breakdown

1500 n. mi. DESIGN RANGE WITH 100% LOAD FACTOR



*60¢/GAL FUEL COST

- 12.2 FT DUAL-ROTATION 4 BLADED PROPFAN
- PROPELLER EFFICIENCY INCREASE = 5%
- ADJUSTED COSTS
  LABOR, MATERIAL & ACQUISITION
- RESIZED AIRPLANE
- ADVANCED TECHNOLOGY ENGINE WEIGHTS

	BASE	W/DUAL ROTATION
TAKEOFF G.W. ~ lb	217 466	213 843
PROPULSION SYSTEM WT- lb	15 143	14 092
FLYAWAY COST – $	14.15M	14.18M

Figure 28.—Advanced technology potential

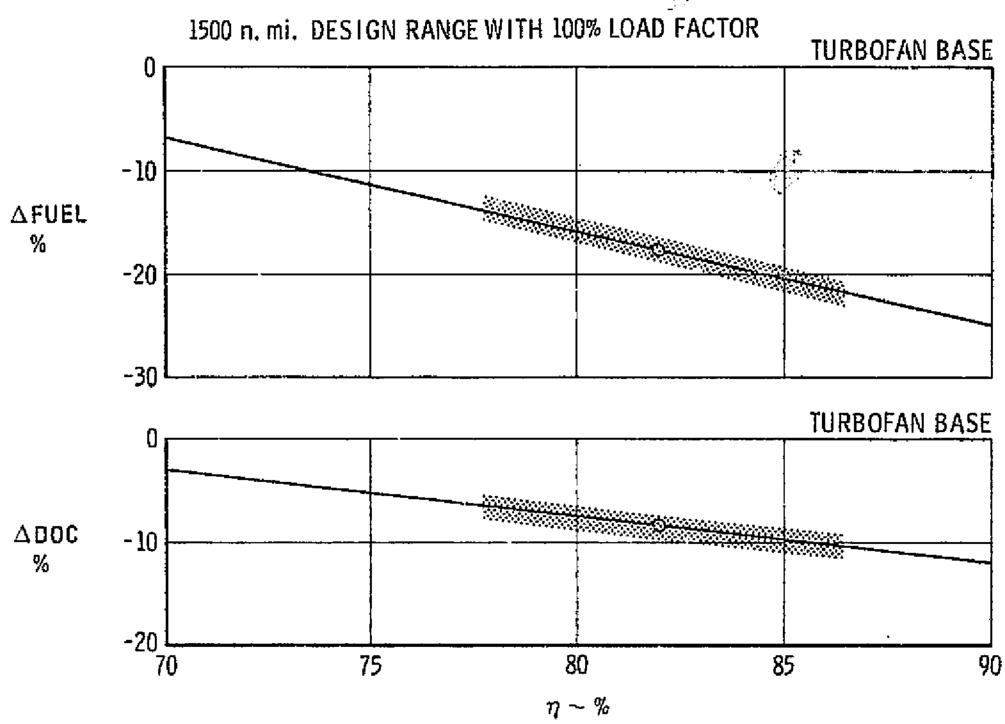


Figure 29.—Sensitivity - propeller efficiency

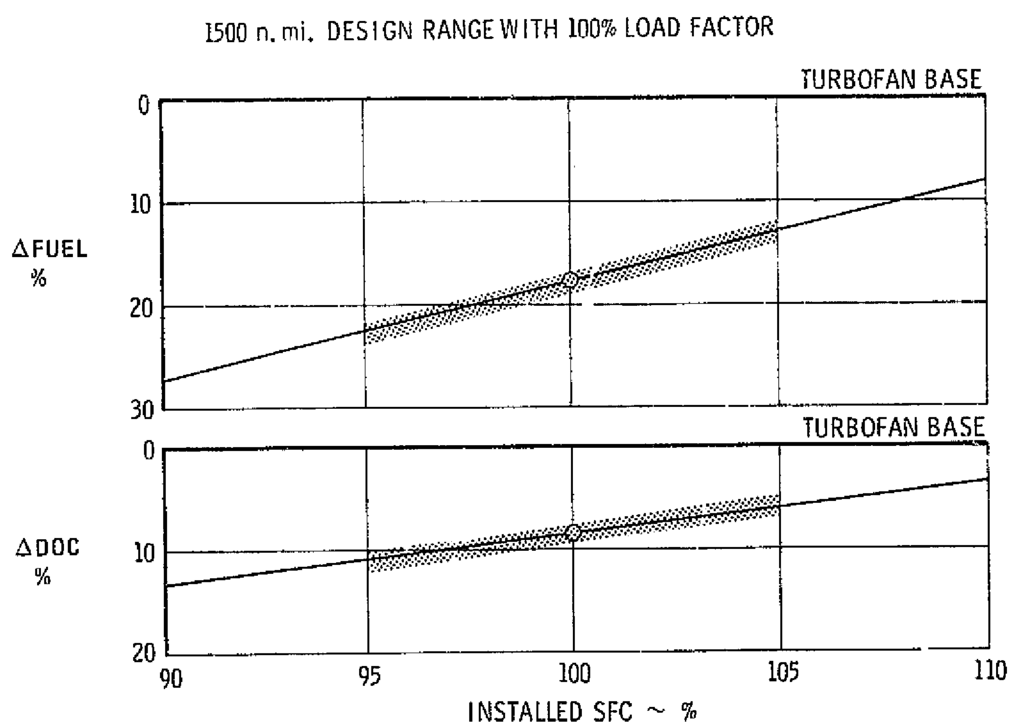


Figure 30.—Sensitivity - engine SFC

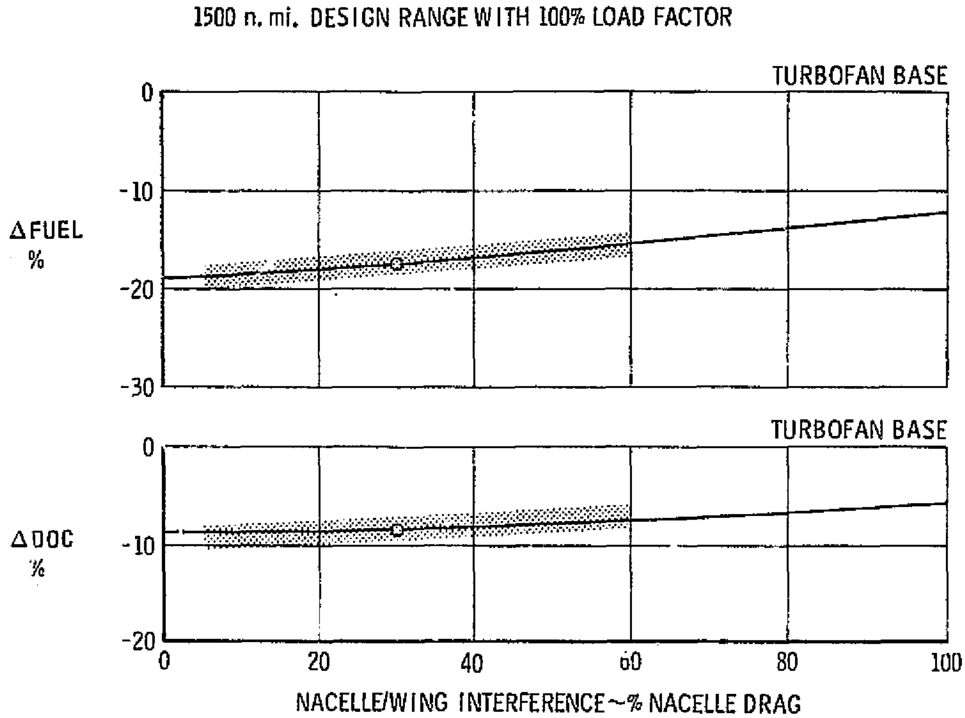


Figure 31.—Sensitivity - nacelle/wing interference

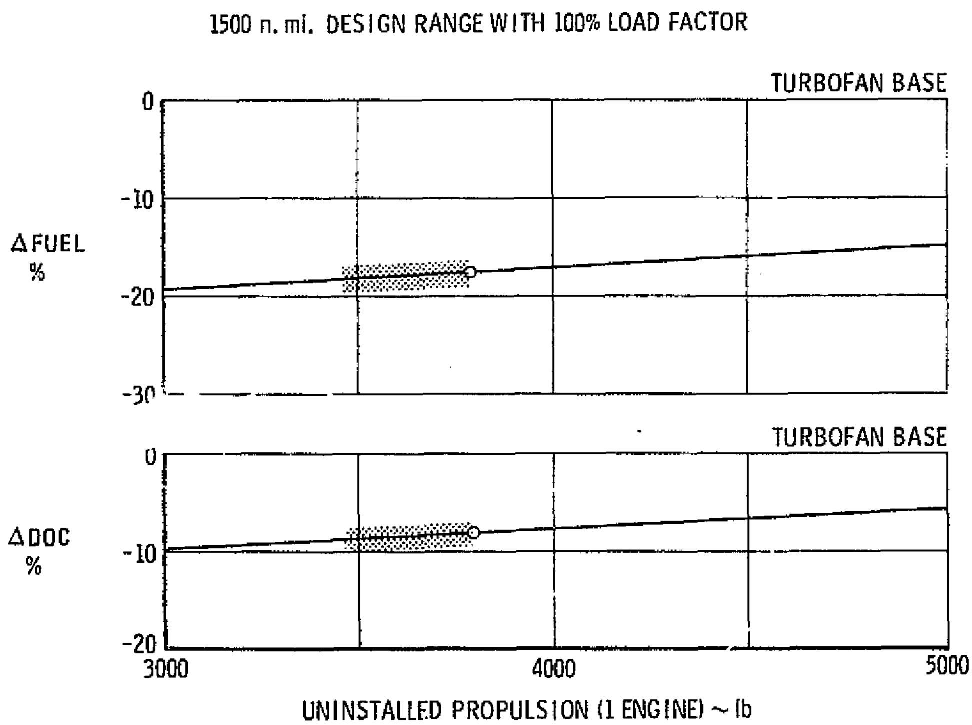


Figure 32.—Sensitivity - propulsion system weight

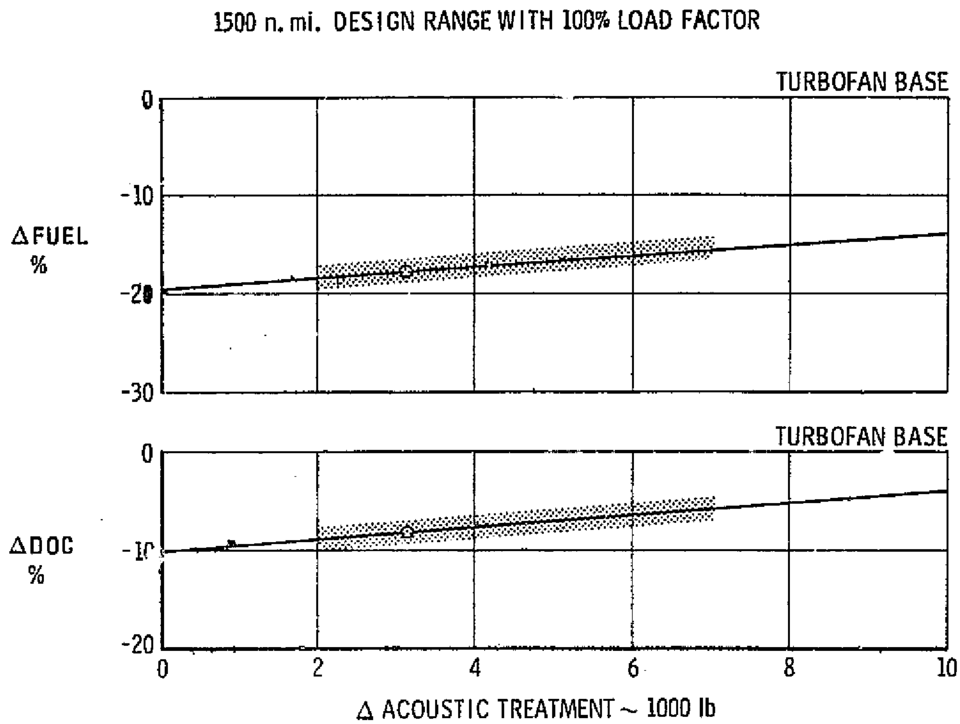
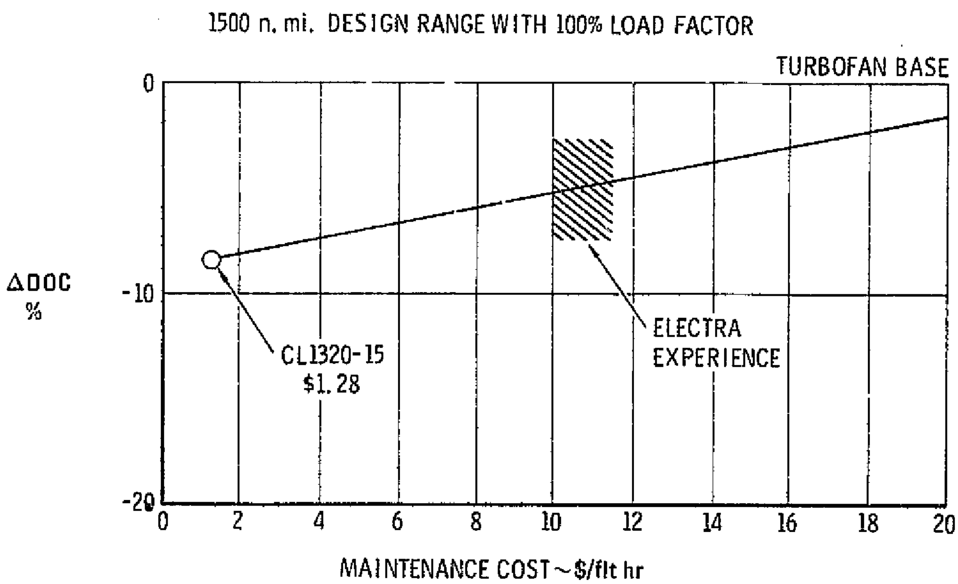


Figure 33.—Sensitivity - interior noise



PROPELLER AND GEARBOX LABOR AND MATERIAL
MAINTAINANCE COST WITHOUT BURDEN

Figure 34.-Sensitivity - propeller and gearbox maintenance cost

TABLE 42.- PROPFAN AIRPLANE CHARACTERISTICS

Weights	CL 1320-15 (Propfan)	CL 1320-11 (Turbofan)
Maximum takeoff gross weight (lb)	217 466	217 015
Maximum landing gross weight (lb)	205 000	205 000
Operational empty weight (lb)	146 417	138 402
Maximum fuel capacity (lb)	50 000	50 000
Powerplants		
Number & Type	4 STS 476 rematch	4 JT10D-2 (Scaled)
Propeller	12.6 ft/8 bladed	--
SLS thrust/engine (lb)	14 135 (8863 shp)	14 672
Body		
Length (ft)	155.8	155.8
Maximum diameter (in.)	235	235
Accommodations (No. Pax)	200 (10/90%) 8 abreast	200 (10/90%) 8 abreast

Wing and Empenage

	CL 1320-15 (Propfan) Wing	Horizontal Tail	Vertical Tail	CL 1320-11 (Turbofan) Wing
Area (sq ft)	1995	284	261	1955
Aspect ratio	10	5	1.6	10
Span (ft)	141.3	37.7	20.4	139.8
Sweep (deg)	25	25	32	25
Mac (in.)	186	97.5	165.6	184

TABLE 43.- ENGINE FEATURES

	Propfan/Turboprop P&W STS 476 Rematch (Scaled)	Turbofan P&W·JT10D-2 (Scaled)
• Description	Turboshaft Engine of Comparable Technology to JT10D-2. New Compressor and LP Turbine. Engine Rescheduled to Meet LCC Requirements	Twin Spool. Design Fan Pressure Ratio of 1.69 and Bypass Ratio of 5.4. Single Stage Fan, 12 Stage Comp. 2 Stage HP Turbine, 4 Stage LP Turbine
• Scaling Factor	0.964	0.618
• Installed Rating		
Thrust (SLS, STD.) - lb	14 135	14 672
shp (SLS, STD.) - hp	8 863	
Max shp (250 KEAS, SL, + 18°F) - hp	10 488	
• Overall Pressure Ratio 36 000 ft M = 0.80 Cruise	20:1	28:1
• Max Combustor Exit Temp °F	2400	2400
• Engine Length - in.	84.3	97.8
• Engine Diameter - in.	21.8	52.6

TABLE 44.- EMPTY WEIGHT BREAKDOWN

Item	Propfan		Turbofan		Comment
Wing		24 368		23 563	Torsional loads
Tail		2 301		2 229	
Body		35 023		34 873	
Landing gear		10 071		10 050	
Flight controls		3 018		3 013	
Nacelles		2 819		1 997	Propeller loads
Propulsion system		16 471		13 436	
Engines (4)	8 408		10 497		
Propellers (4)	4 380		-		
Gearboxes (4)	2 360		-		
Air intake	311		390		Smaller turboprop inlet
Exhaust	191		1 715		Plain tailpipe vs fan reverser
Misc.	621		834		
Furnishings		24 870		21 761	Acoustic treatment
Electrical		5 017		5 008	
Air conditioning		4 349		4 349	
Misc		5 148		5 142	
M.E.W.		133 455		125 441	
		6.4%			

TABLE 45.- FRICTION DRAG BREAKDOWN

M 0.80 at 30 000 feet $q = 282$ lb/ft^2

	Propfan Turboprop		Turbofan		
Component	D/q	C_D	D/q	C_D	Comment
Fuselage	15.423	0.00773	15.423	0.00789	
Wing	11.848	0.00594	12.417	0.00635	Wing/Nacelle interface and slipstream effects
Horizontal tail	1.625	0.00081	1.571	0.00080	
Vertical tail	1.822	0.00091	1.768	0.00090	
Nacelles	2.808	0.00141	1.691	0.00086	Wing/Nacelle interference
Pylons	-	-	0.662	0.00034	Turbofan only
Total D/q	33.526		33.532		
Friction D (lb)	9 454		9 456		

TABLE 46. —SUMMARY - PROPFAN/TURBOFAN PERFORMANCE COMPARISONS

	1500 n.mi. Design Range 100% LF			@475 n.mi. 58% LF
	Propfan CL 1320-13	Turbofan CL 1320-11	% Change	% Change
Takeoff Gross Weight - lb	217 466	217 015	+0.2	
Block Fuel - lb	23 390	28 466	-17.8	-20.4
DOC (30¢/gal Fuel) - ¢/ASM	1.310	1.384	-5.3	-5.9
DOC (60¢/gal Fuel) - ¢/ASM	1.660	1.809	-8.2	-8.5
Takeoff Field Length - ft	4650	5578	-16.7	
Landing Field Length - ft	6057	6159	-1.6	
Flyaway Cost - M$	14.15	13.39	+6.0	

8. CONCLUSIONS AND RECOMMENDATIONS FOR TECHNOLOGY DEVELOPMENT AND FUTURE STUDY EMPHASIS - TASK 8

Lockheed's role in the basic study did not include participation in the air transportation system synthesis and evaluation task once the refined aircraft performance and operating cost data had been made available to the consultant organization. The analysis required to define the selected options, however, leads to the conclusions and recommendations discussed in the following paragraphs.

The first classification of fuel conserving options studied, changes to current aircraft operational procedures, can offer significant fuel savings benefits even though on an individual basis the fuel savings may be quite small. This is because implementation of procedure changes can be made on an immediate basis and on a large number of aircraft resulting in large cumulative savings over a period of time. Continued use of those operational procedures already implemented by many of the airlines is recommended. The operators with the support of the manufacturers should continue to pursue the implementation of additional procedure changes within the current air traffic control system. Since the most significant additional savings which can be obtained through changes in operational procedures are dependent on changes to the air traffic control system, it is recommended that studies be made to investigate the required improvements. This would allow a complete benefits analysis to be made which could aid in determining the direction to be taken in air traffic control in the future.

Of the L-1011 modifications considered, the revised engine afterbody and modest wing-tip extension offer even larger fuel savings on an individual aircraft basis than operational procedure changes. The possibility of retrofit of these options also provides the benefit of large cumulative savings. Strong consideration should be given to fleet retrofit of these options. In the case of the engine afterbody, general incorporation is recommended. The wing tip extension of the type studied should be retrofitted to those aircraft whose operators can accept the takeoff weight restriction penalty.

Increased seating density offers the largest potential fuel savings of the modifications studied but is dependent on continued increases in demand and on passenger acceptance. This type of modification is an option currently available to the airline operators. It requires no extensive research activity and involves minimum investment cost. In a limited fuel availability environment, increased seating density may become a requirement.

Derivatives of current aircraft are also dependent on demand in that the most beneficial appear to be high passenger capacity, stretched fuselage variants. The possible fuel savings must be traded against development cost and thus purchase price. In the time period studied (before 1980) only limited incorporation of fuel conservation technology is possible. For later service a greater degree of fuel conservation technology incorporation would result in considerably more cost effective derivatives.

The new near-term aircraft studied do not offer as significant fuel savings as the high-density derivative on a seat-mile basis, nor do they offer operating costs sufficiently lower to encourage purchase. When designed with minimum block fuel as the design criterion these aircraft may not be compatible with the current fleet. As with the derivative aircraft, a somewhat later introduction date may offer a beneficial alternative by allowing more of the fuel conservative technologies to be incorporated.

One of these technologies, the advanced turboprop propulsion system, would require a delay in introduction beyond the 1980 date specified by the basic contract Statement of Work. Because the potential of this propulsion system appeared to be so promising, a supplemental study contract was added to allow a more detailed study, including comparison with an equally advanced (1985) turbofan aircraft.

The results of this comparison study show that an advanced turboprop propulsion system is a viable alternative to the turbofan. The swept wing propfan/turboprop airplane offers a means of exploiting the inherent efficiency advantage of the turboshaft engine at the higher cruise speeds and altitudes required in today's air traffic environment. When compared on an equal technology and equal design mission basis, advanced turboprop airplanes offer significant fuel and operating cost savings over the equivalent turbofan airplane. These efficiencies can be obtained without compromise to passenger comfort.

As a result of this study the following recommendations for further research should be considered on a first priority basis to verify the concepts theorized here.

1. Demonstrate propeller efficiency levels of approximately 80 percent (installed) at a flight Mach number of 0.80.

2. Perform experimental investigations of propfan/turboprop wing integration to establish that reasonable drag characteristics exist for practical propfan/turboprop power plants mounted on swept, supercritical wings.

3. Determine sound levels generated by propfan/turboprop concepts operating at Mach 0.80 cruise and establish sound attenuation and weight penalty requirements for their satisfactory suppression.

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